USAAVLABS TECHNICAL REPORT 67-24

INVESTIGATION OF THE FEASIBILITY OF BURNING EMULSIFIED FUEL IN GAS TURBINE ENGINES

March 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

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The objective of the efforts reported herein was to determine the feasibility of operating gas turbine engines on emulsified fuel. However, some of the engine companies attempted to evaluate the emulsion itself and to offer recommendations as to how the emulsion could be improved. Thus, some of the results obtained and recommendations and conclusions given as they concerned a particular engine were not in keeping with the overall objective of these limited efforts.

The emulsified fuel used in these tests was not an optimum emulsion; however, at the time these contracts were awarded, the emulsion used was the best available.

Since these initial efforts, contracts have been awarded to two commercial organizations to develop an emulsion which meets the criteria set forth for use with Army aircraft.

Task 1F121401A529

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SUMMARY

This report discusses the results of five different gas turbine engines operating on emulsified JP-4 fuel. Problems associated with using emulsified fuel, and the conclusions and recommendations as they pertain to each individual engine, are given.

The results of these studies indicate that it is feasible to operate a gas turbine engine on emulsified JP-4 fuel. Several areas in which further research is needed, as recognized by the engine companies, are brought out in the report.

FOREWORD

This report combines the work of Continental Aviation and Engineering Corporation, Contract DA 44-177-AMC-369(T); Allison Division of General Motors, Contract DA 44-177-AMC-428(T); General Electric Company, Contract DA 44-177-AMC-452(T); and Lycoming Division of AVCO Corporation, Contracts DA 44-177-AMC-453(T) and DA 44-177-AMC-457(T). It consists of the studies conducted by the above engine companies to determine the feasibility of burning emulsified fuel in a gas turbine engine.

A section listing general conclusions and recommendations as they pertain to the objectives of the program and as experienced by the engine companies is given at the conclusion of the report.

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LIST OF SYMBOLS FOR PARTS 1 AND 2

PART 1

N_g	Gas generator control speed, revolutions per minute
P_2	Compressor inlet pressure, pounds per square inch
P_3	Compressor discharge pressure, pounds per square inch
PLA	Power lever angle
PPH	Pounds per hour
T_2	Inlet air temperature, degrees Fahrenheit
T_5	Gas generator turbine discharge temperature, degrees Fahrenheit
T_7	Exhaust nozzle inlet temperature, degrees Fahrenheit
W_f	Control metered fuel flow, pounds per hour
β	Condition lever, degrees
θ	Ratio of T_2 to 59°F
δ_2	Ratio of barometric pressure ("H_g) to 29.92"H_g
η_{BR}	Burner efficiency
P	Fuel nozzle primary flow, pounds per hour
S	Fuel nozzle secondary flow, pounds per hour

PART 2

C.D.P.	Compressor discharge pressure
E.D.S.	Engineering Design Specifications (Allison)
°F.	Degrees Fahrenheit
N_1	Gas producer rotational speed in r.p.m.

N_2	Power turbine rotational speed in r.p.m.
P_c	Compressor discharge pressure signal
p.p.h.	Pounds per hour
p.s.i.	Pounds per square inch
p.s.i.g.	Pounds per square inch gauge (above barometric pressure)
r.p.m.	Revolutions per minute
T.M.O.P.	Torquemeter oil pressure
T.O.T.	Turbine outlet temperature (power turbine inlet temperature)
θ	Standard compressor inlet temperature correction factor
δ	Standard compressor inlet pressure correction factor

PART 1. GENERAL ELECTRIC, T-64

by
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INTRODUCTION

Aircraft fires account for 15 percent of the fatalities in airline accidents. Of the fatalities in Army helicopters destroyed by fire, 65 percent were due to the fire and not the crash itself. These facts have led to studies to find fuels which would reduce the hazard of postcrash fires.

One method of achieving this is to use emulsified fuels, where the vaporization rate is greatly reduced due to the reduced dispersion of the fuel on impact. Should a fire occur, it is usually confined and slow burning, thereby eliminating the fireball effect experienced with JP-4.

The emulsion tested was known as JD-1 and was manufactured by the Western Company, Dallas, Texas. The emulsion consists of 0.5 percent MFE-10, 2.5 percent water, and 97 percent JP-4. See Figure 1. This emulsion had previously been tested on an Allison T63 turboshaft engine and a Lycoming T53 turboshaft engine.

The object of the tests conducted by General Electric was to ascertain if the T64 engine could be started and operated using the emulsified fuel and to ascertain if this fuel had any deleterious effects on the engine hot section.

The engine used for the test was a production engine 263012-2 which had logged 505 hours 45 minutes of operation in use on the CV-7A aircraft before the safety fuel test.

TEST PROGRAM

The test program was divided into two parts.

1. Bench Test of Fuel System

    a. The fuel control, flow divider, variable geometry actuators, manifolds, and nozzles were mounted on a

bench test stand in the order in which they are mounted on the engine.

b. A bench test to General Electric Specification M50T1675-S1 (details and results of which are shown in Appendix 1) was conducted on the fuel control, the fuel used for the test being JP-4.

c. The spray pattern of the nozzles spraying JP-4 was examined and a motion picture film made of the spray.

d. A major problem with emulsion fuels is the removal of contamination from the fuels. Contamination, which in JP-4 would separate out of the fuel, is held in suspension by JD-1. To aggravate the situation, JD-1 is extremely good at removing dirt and scale from fuel lines, which would otherwise cling to the walls of the fuel lines; all the lines from the various portions of the fuel system were connected together and purged by pumping emulsified fuel through them.

e. The pipes were then reconnected to the fuel system and the emulsified fuel was pumped through the system. An acceleration limit calibration curve with $T_2 = 69^oF$ was conducted using JD-1 as the fuel. The fuel flow was measured by a turbine type flowmeter and an Eput recorder. The flowmeter was located between the fuel control and flow divider. As the calibration for the flowmeter was applicable only to JP-4, a re-calibration was conducted for the emulsified fuel using the weight/time method. See Figure 5. The flowmeter was more accurate at measuring the emulsified fuel at the higher flows than at the lower flows. For example, at 200-pph actual flow of JD-1, the meter read 10 percent too low; at 1600 pph, the meter read 1.25 percent too high.

f. Motion picture films were made of the fuel control operating on emulsified fuel and also of the emulsified fuel being sprayed through the fuel nozzles.

g. The spray pattern of the emulsified fuel was considered sufficiently good to support combustion in the T64 engine, and the engine test was carried out.

2. Engine Test

By agreement with the U. S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, the engine was tested as a gas generator to simplify the test results, giving similar characteristics on the hot section.

a. The engine was motored and checked for vibrations, leaks, lube pressure, etc.

b. The engine was started operating on JP-4, and an idle inspection and engine mechanical checkout were conducted, resulting in normal engine operation.

c. A 5-point calibration was then conducted at the following engine conditions, the engine operating on JP-4:

Idle	77% $N_g/\sqrt{\theta}$
	1000°F T_5
Normal	1080°F
Military	1130°F
Maximum	1155°F

d. Sanborn oscillographic recording traces were taken while the engine performed the following transients:

1) A burst to maximum followed by a chop to idle.

2) Bursts to maximum and chops to flight idle.

e. The emulsified fuel line was then hooked up to the fuel pump inlet, the fuel system being primed on JP-4.

f. The engine was started on the JP-4 and converted to operating on emulsified fuel as the JP-4 in the controls was replaced by the incoming emulsified fuel. There was no change in the engine operation while the transition occurred. See Figure 9.

g. A 5-point calibration such as that in c, above, was conducted with the engine running on emulsified fuel.

h. The JP-4 supply line was reconnected to the fuel pump inlet and the engine was started and run on JP-4. A 5-point calibration identical to c was conducted to ascertain if any deterioration in engine performance was experienced as a result of flowing the emulsified fuel through the engine fuel system. All three calibrations were conducted with anti-icing flow inadvertently left on.

When the anti-icing valve is open, 1 percent anti-icing air flow is introduced into the compressor inlet through the inlet guide vanes and therefore downstream of compressor inlet air temperature measurement. This results in actual inlet air temperature approximately 6°F higher than measured inlet air temperature. The data from all three calibrations was adjusted for the actual inlet air temperature and the performance results were identical with the subsequent calibrations conducted with anti-icing air off.

i. The engine was allowed to stand idle over a weekend shutdown with JP-4 in the engine fuel system. The emulsified fuel line was connected to the fuel pump inlet. The complete engine fuel system was purged of JP-4 and primed with JD-1.

j. A successful start on emulsified fuel alone was achieved with the engine cold. The event was recorded on Sanborn oscillographic equipment. See Figure 10.

k. Seven successive starts with emulsified fuel only were then attempted, and each time the start was successful.

l. Transients were performed with the engine running on emulsified fuel. A burst from idle to maximum was made and then a chop to ground idle. See Figures 12 and 13. A slow acceleration to maximum and a slow deceleration to ground idle were also conducted.

m. A 5-point calibration was conducted with the engine operating on JD-1. This calibration procedure was identical with g, except that the anti-icing valve was off. These results are shown in Figures 6 and 7. When the initial calibration data in c was adjusted for the 1 percent anti-icing air flow as defined in h, the results were identical with the results of this calibration.

n. The total engine running time on JD-1 was 3 hours 12 minutes. Fifteen starts were made on JD-1. Two of these were made with the engine cold. One of these cold starts is described in paragraph i above. For the other cold start, the fuel control was allowed to stand primed with JD-1 overnight (13 hours 18 minutes). A successful start was then achieved on JD-1 alone.

o. A final calibration was conducted with JP-4 and with the anti-icing flow off. On completion of the test, the engine hot section was torn down.

   The results of the final calibration are shown in Figures 6 and 7. When the initial calibration data in c was adjusted for the 1 percent anti-icing air flow as defined in h, the results were identical with the results of this calibration.

ENGINE TEARDOWN

The engine exhaust cone, gas generator rotor, and combustion chamber liner were removed from the engine.

Examination of these components showed that the emulsified fuel had no deleterious effects on any of the components. In fact, there were no signs that the engine had been operated on a fuel other than JP-4.

The fuel control, flow divider, and nozzles were bench tested. The fuel control bench test showed that JD-1 had no deleterious effects on the control. The flow divider and nozzles did not meet all their specification limits. See Appendixes II and III.

EXPERIMENTAL RESULTS

Curves of the corrected thrust (F/δ_2) and corrected T_7 (T_7/θ_2) against corrected fuel flow are shown in Figure 6. The values are for the calibrations with the anti-icing off.

Compressor pressure ratio(P_3/P_2) and burner efficiency (η_{BR}) are shown in Figure 7.

EVALUATION

The bench test of the fuel control and nozzles indicated that it would be possible to operate the engine on emulsified fuel, and this was confirmed by the engine test.

When the emulsified fuel was pumped through the fuel system, the shearing forces in the system broke the emulsion down so that a mixture of approximately half liquid fuel and half emulsified fuel was discharged from the nozzles. It was visibly evident that the spray pattern had streaks of emulsified fuel intermingled with the liquid fuel (Figures 2 and 3). This streaky spray pattern had no effect on combustion efficiency during the engine test as determined by performance results. See Figure 7.

An emulsion residue was left on the nozzle after the fuel supply was shut off (Figure 4).

The experimental results indicate that operating the engine on emulsified fuel JD-1 had no effect on the engine's overall performance. See Figures 6 and 7.

The curves of corrected thrust (F/δ_2) and corrected T_7 (T_7/θ_2) against corrected fuel flow show that there was no effect on either parameter.

The results also show that there was no loss in compressor pressure ratio (P_3/P_2) and burner efficiency (η_{BR}) when using JD-1 (Figure 7).

The Sanborn oscillographic recordings show that the engine response is slightly slower using the emulsified fuel but is well within the General Electric T64-GE-10 Model Specification E1086. For example, Figures 11 and 12 show the engine performing a burst to maximum with JP-4 and JD-1, respectively.

The time to achieve 95 percent of the speed change was 3.8 seconds with JP-4 and 5.1 seconds with JD-1. The General Electric T64-GE-10 Specification E1086 limit for this transient is 10 seconds.

Figures 8 and 10 show that the time for a start to idle with JP-4 was 27 seconds; with JD-1, the time was 33.7 seconds. The average times for starts taken from the engine log sheets are 27.2 for JP-4 and 30.73 for JD-1. The air impingement starter air pressure was constant for all starts. The General Electric T64-GE-10 Model Specification E1086 limit is 35 seconds.

Although the starting time with JD-1 was greater than JP-4, JD-1 still meets the specification limits at sea level, ambient conditions.

Twenty-fcur T_7 thermocouples were located in the jet pipe to obtain a T_7 profile for the engine operating on each of the fuels. Table I gives a comparison of the profiles, the engine being run at a nominal T_5 of 1130°F.

The arithmetic mean, the range, and the standard deviation of the T_7's are given for JP-4 and JD-1.

TABLE I

T_7 PROFILE COMPARISON

	JP-4	JD-1
Arithmetic mean	1139.2°F	1130.6°F
Range	99°F	89°F
Standard deviation	25.94°F	25.65°F

As shown in Table I, there is no significant difference between the profiles; in fact, the JD-1 profile is slightly more uniform. Visual observation of the engine exhaust stream showed no signs of flame or smoke.

Examination of the hot section hardware revealed no indication of hot or cold spots. In fact, the condition of the hardware was so unaffected by the JD-1 fuel test that it may be assumed that engine hardware will be able to withstand prolonged endurance running.

CONCLUSIONS

1. The T64 engine will operate on JD-1 at sea level static conditions.

2. The engine will operate for a period of at least 3 hours.

3. No loss in engine performance will be experienced during the period.

4. Engine starts and transients while operating on JD-1 will meet the General Electric T64-GE-10 Model Specification E1086 requirements.

5. The engine can be started using only JD-1. No priming with JP-4 or any other fuel will be necessary.

6. No modifications are necessary to the engine or its controls in order to operate it on JD-1.

RECOMMENDATIONS

The test conducted, while meeting with the contractual requirements, was extremely limited. It is recommended that:

1. Further testing be conducted with the engine on JD-1 for a period of at least 50 hours.

2. Testing at conditions other than sea level static conditions be conducted.

3. The testing cover a range of ambient temperature conditions.

4. Combustion chamber component work be conducted to examine the effects of temperature and pressure on the atomization of JD-1.

Figure 1. JD-1 Being Mixed in the Western Pumping Station.

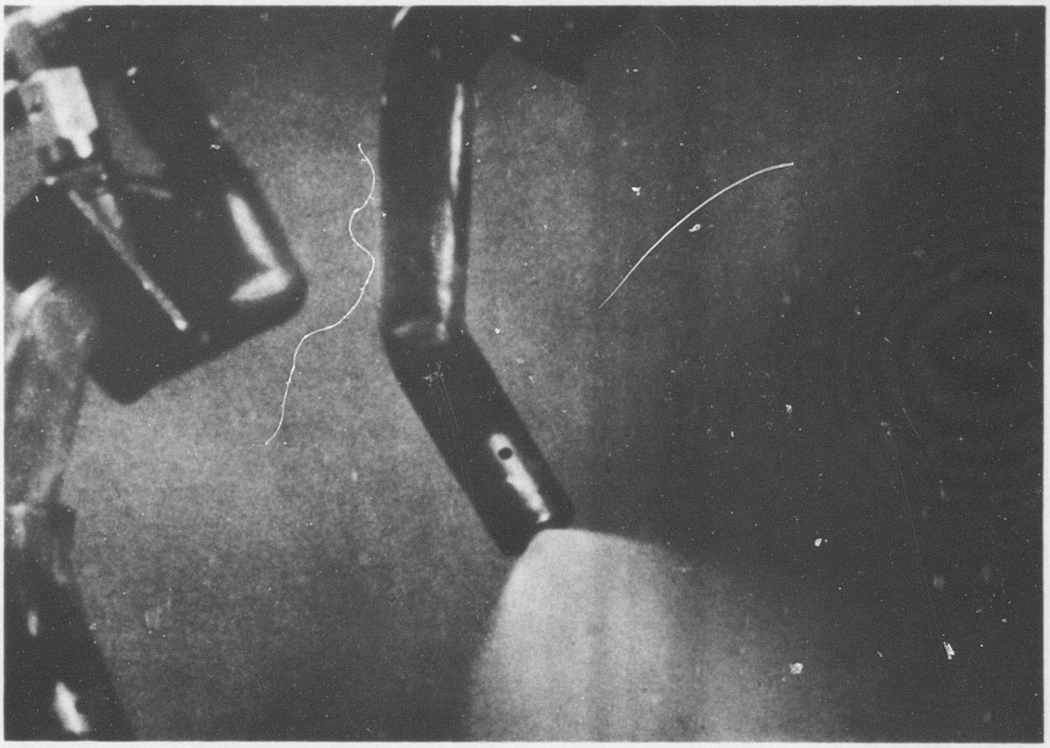

Figure 2. JP-4 Fuel Spray.

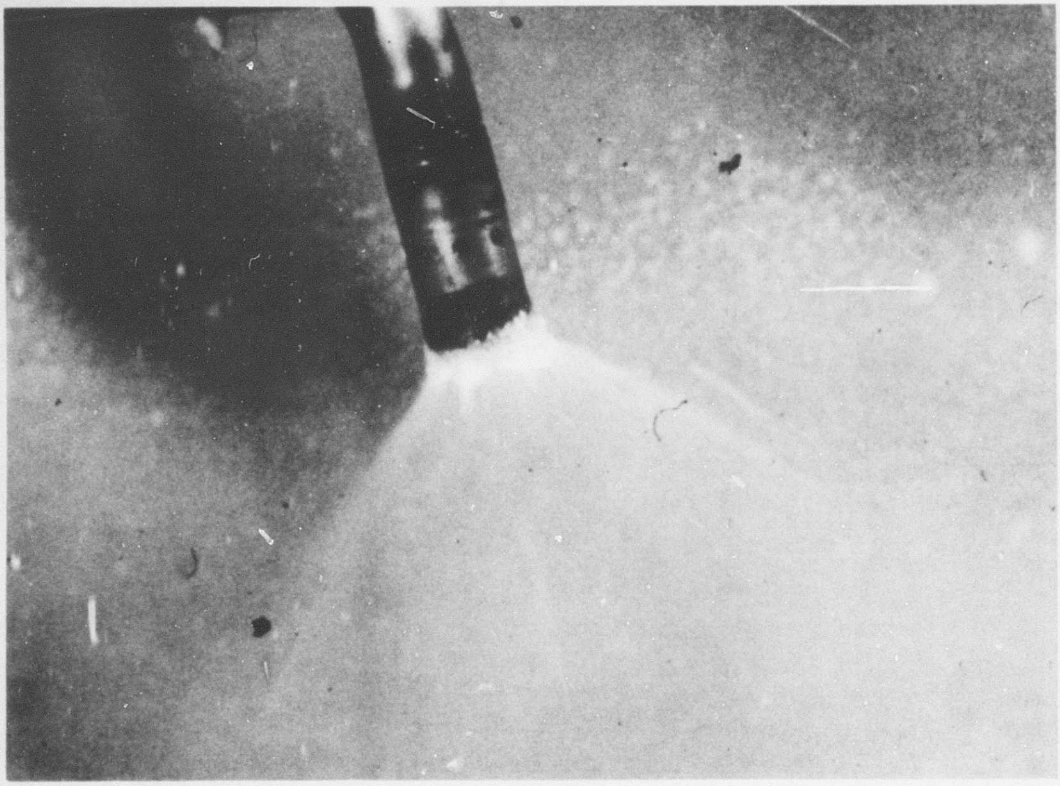

Figure 3. JD-1 Fuel Spray.

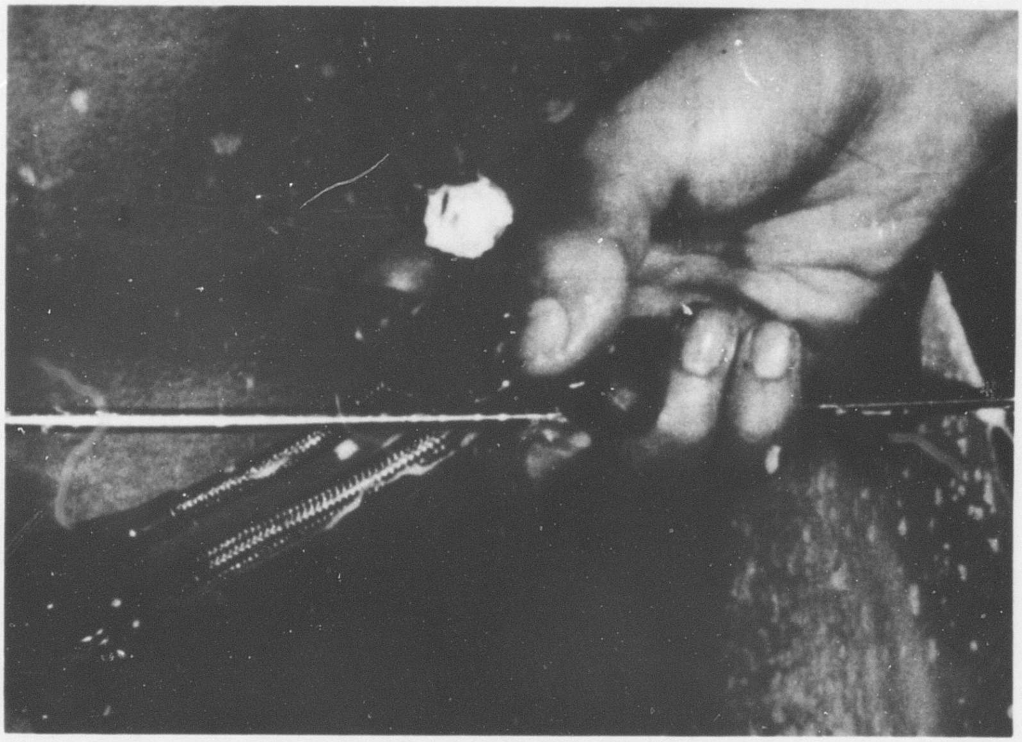

Figure 4. Emulsion Residue on Nozzle After Spraying JD-1.

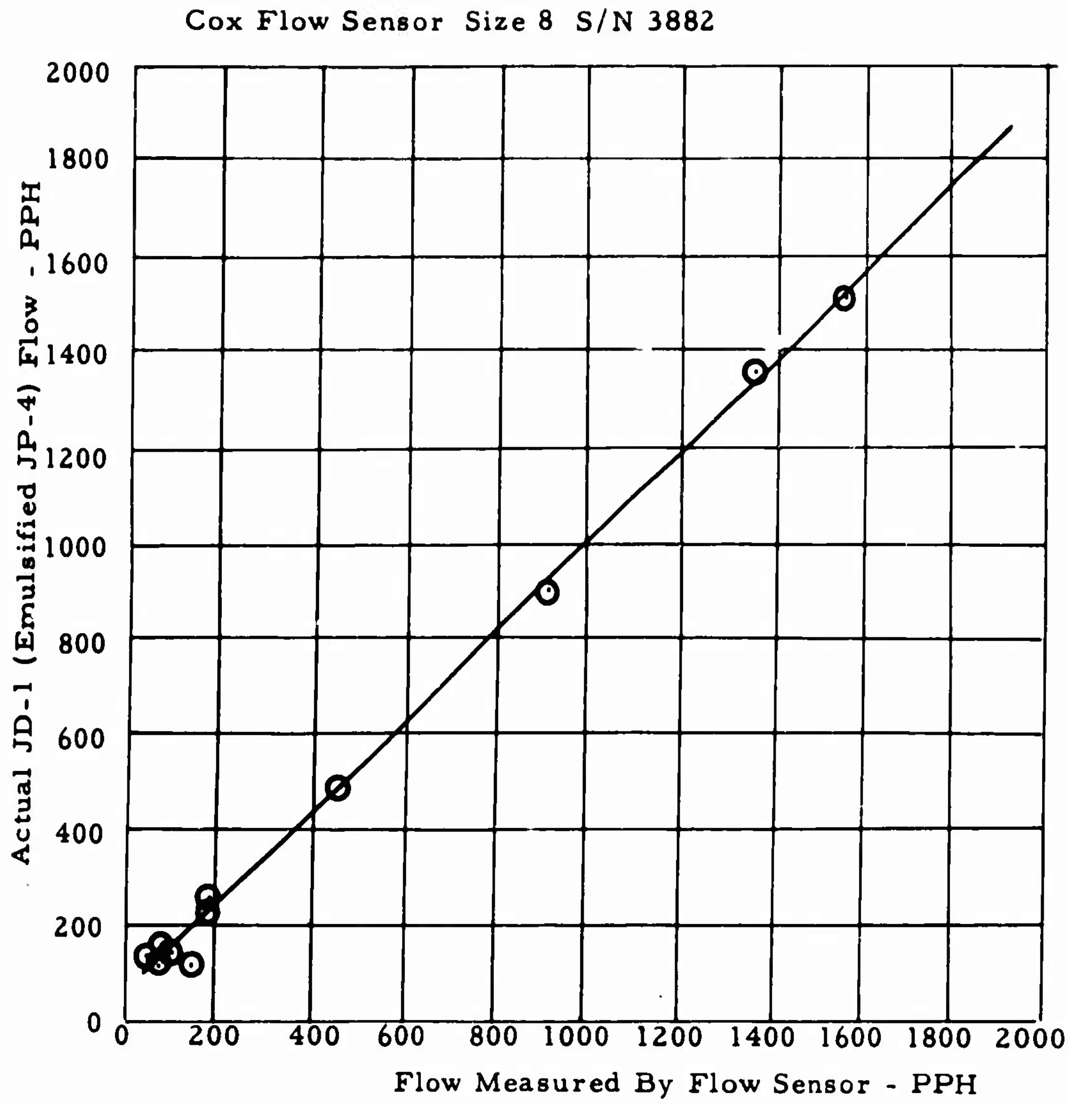

Figure 5. Calibration of Fuel Flow Sensor for JD-1.

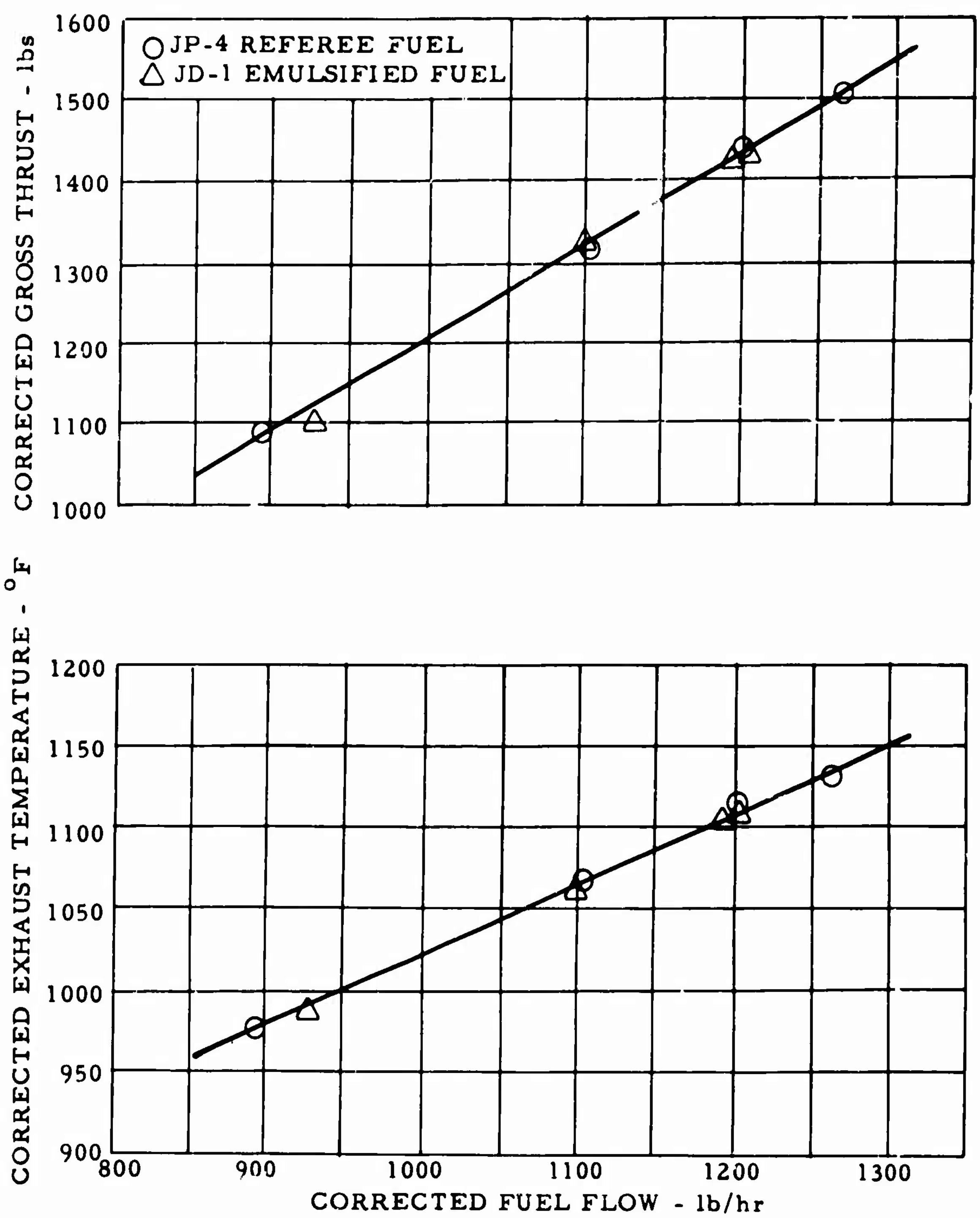

Figure 6. Corrected Gross Thrust and Corrected Exhaust Temperature Vs. Corrected Fuel Flow for JP-4 and JD-1.

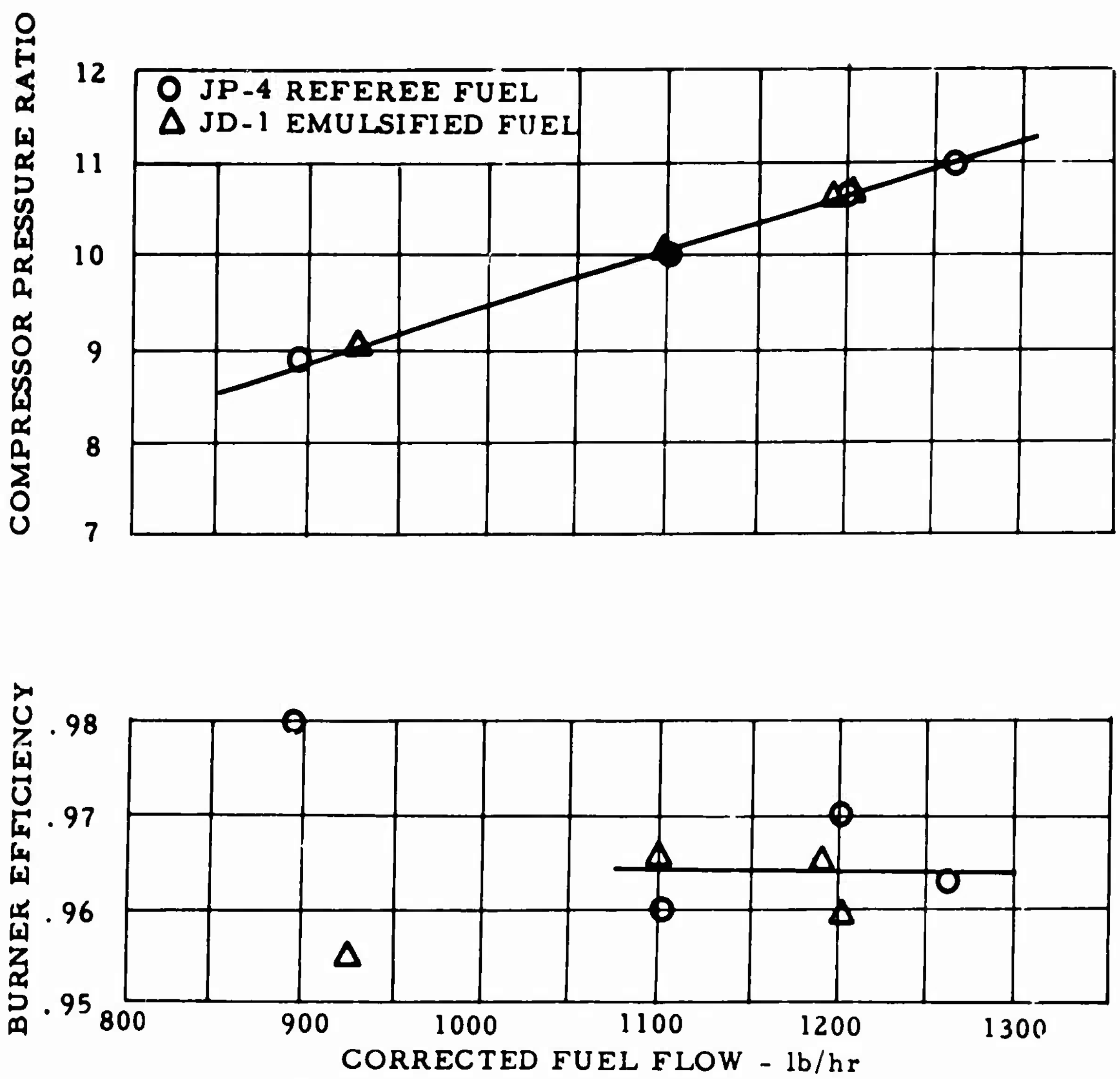

Figure 7. Compressor Pressure Ratio and Burner Efficiency Vs. Corrected Fuel Flow for JP-4 and JD-1.

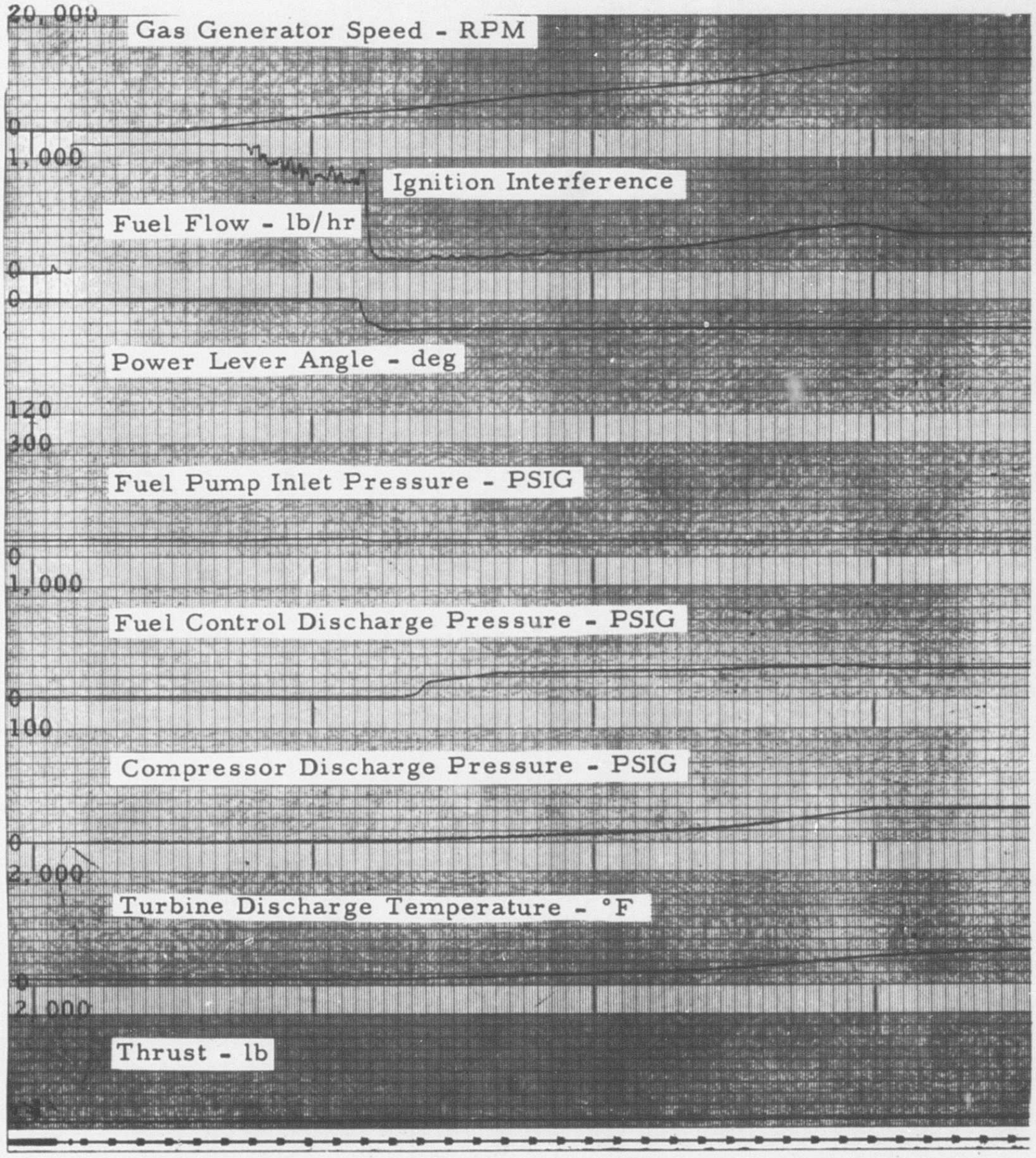

Figure 8. Engine Start on JP-4.

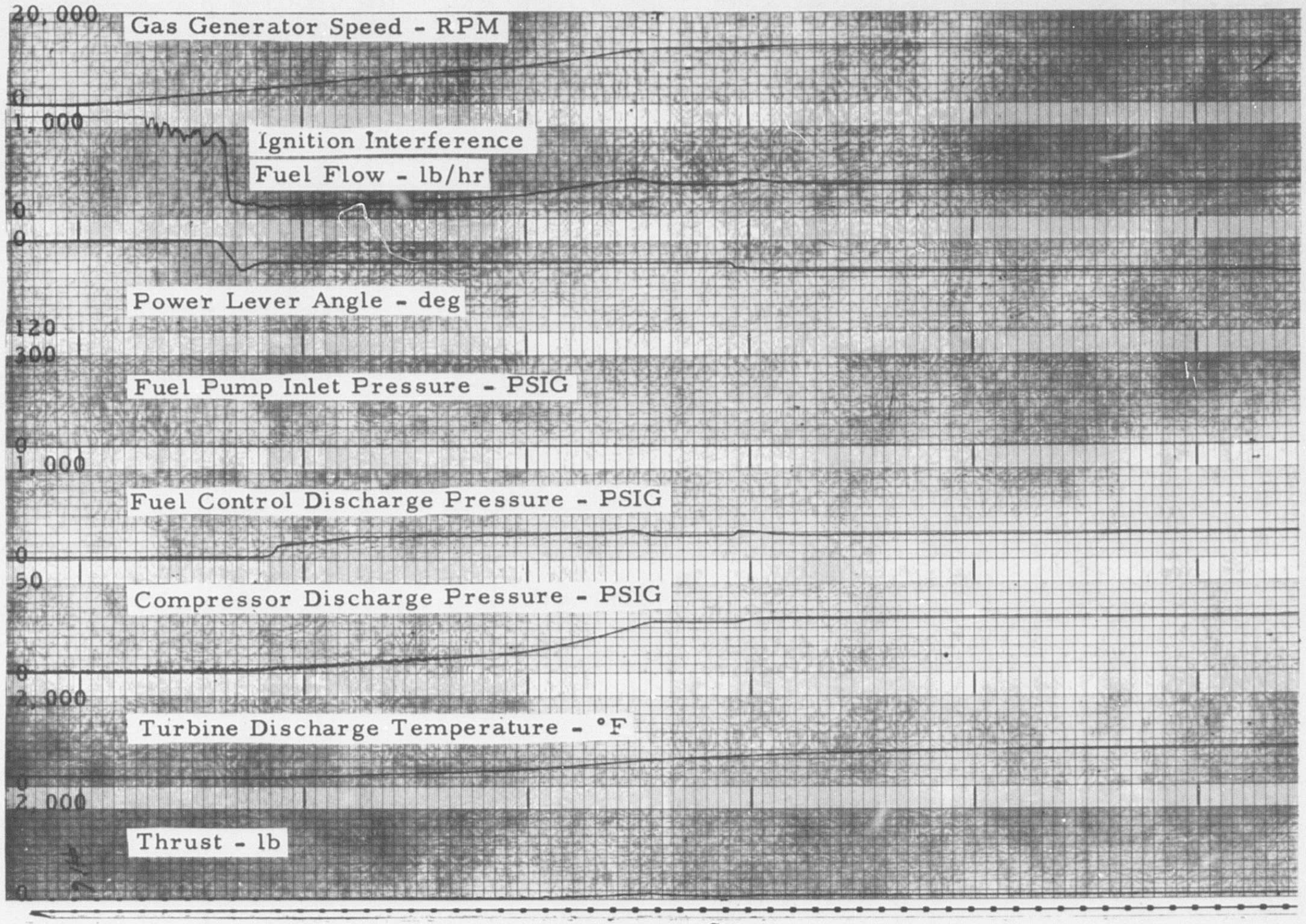

Figure 9. Engine Start With Fuel Control Primed With JP-4 and JD-1 Connected to Fuel Pump Inlet.

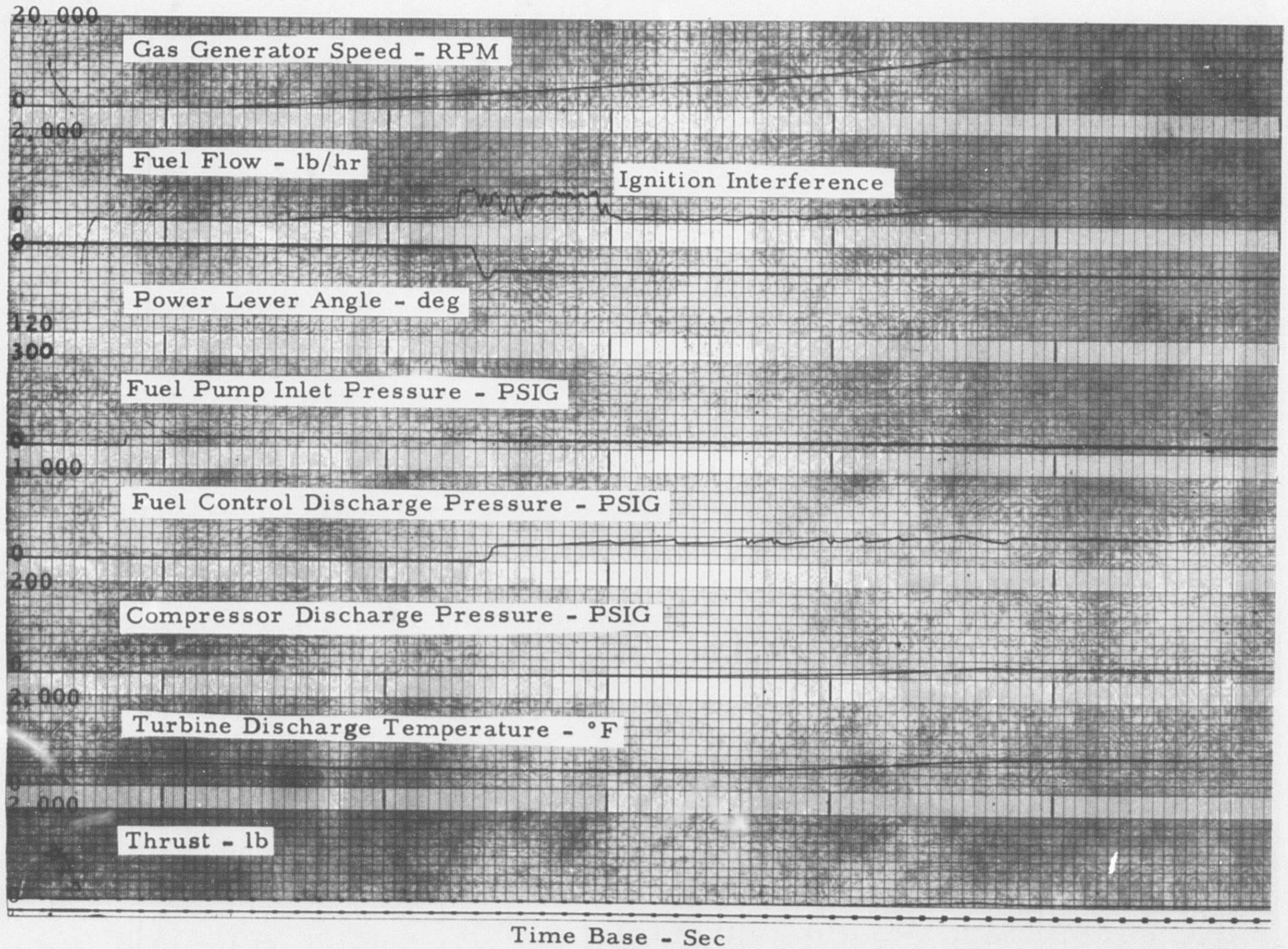

Figure 10. Engine Start on JD-1 (Emulsified JP-4).

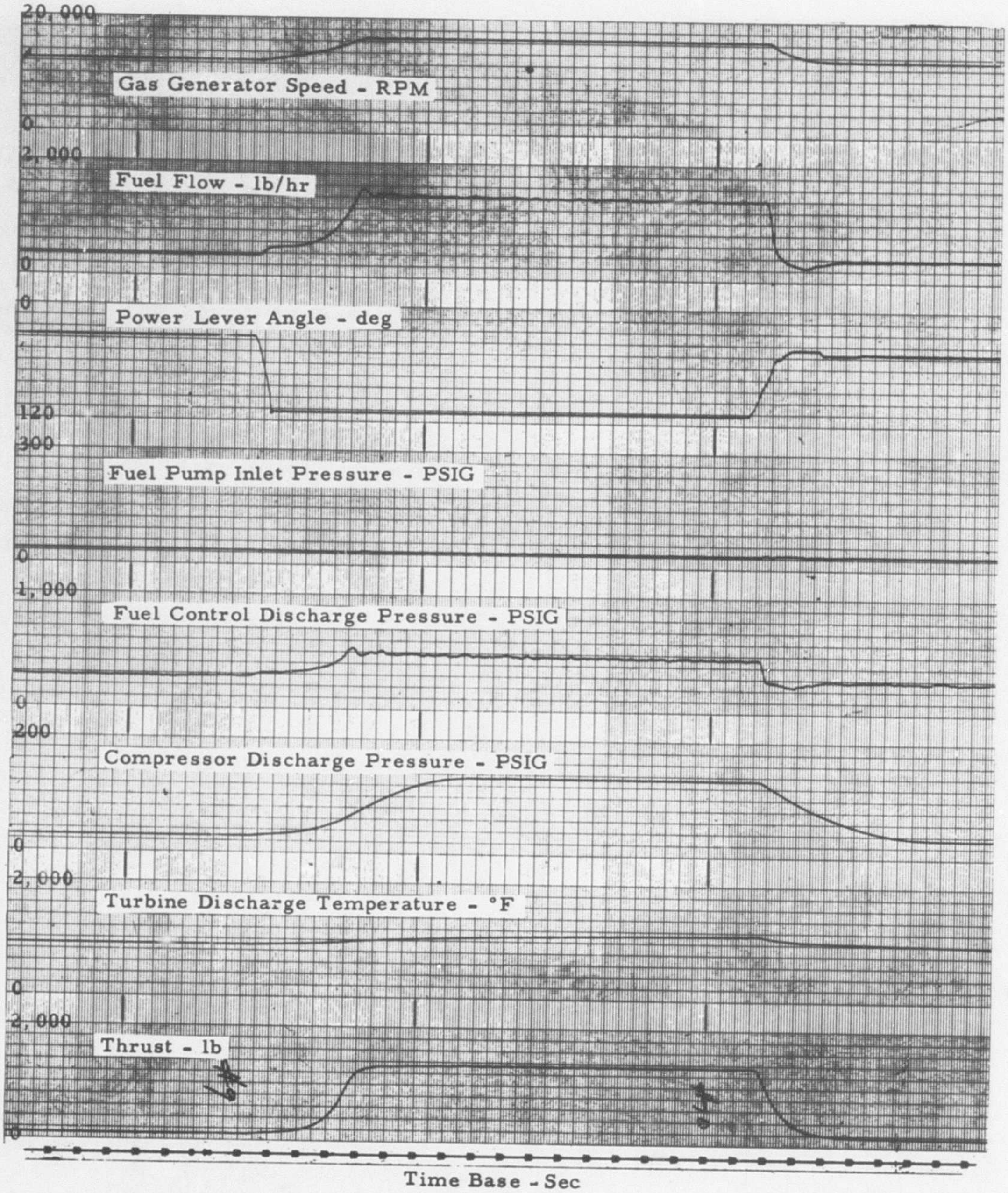

Figure 11. Burst to Maximum and Chop to Flight Idle (JP-4).

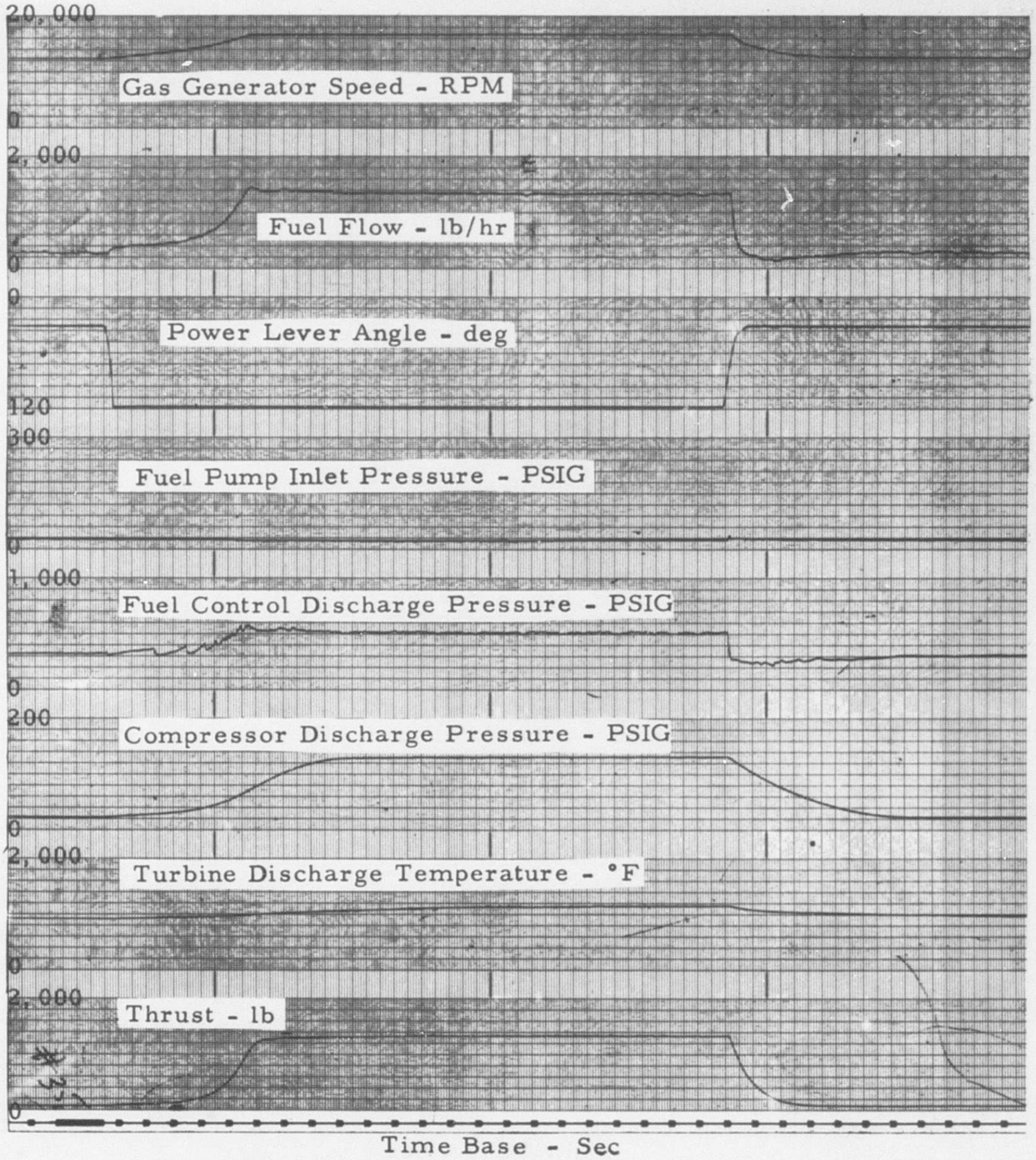

Figure 12. Burst to Maximum and Chop to Ground Idle (JD-1).

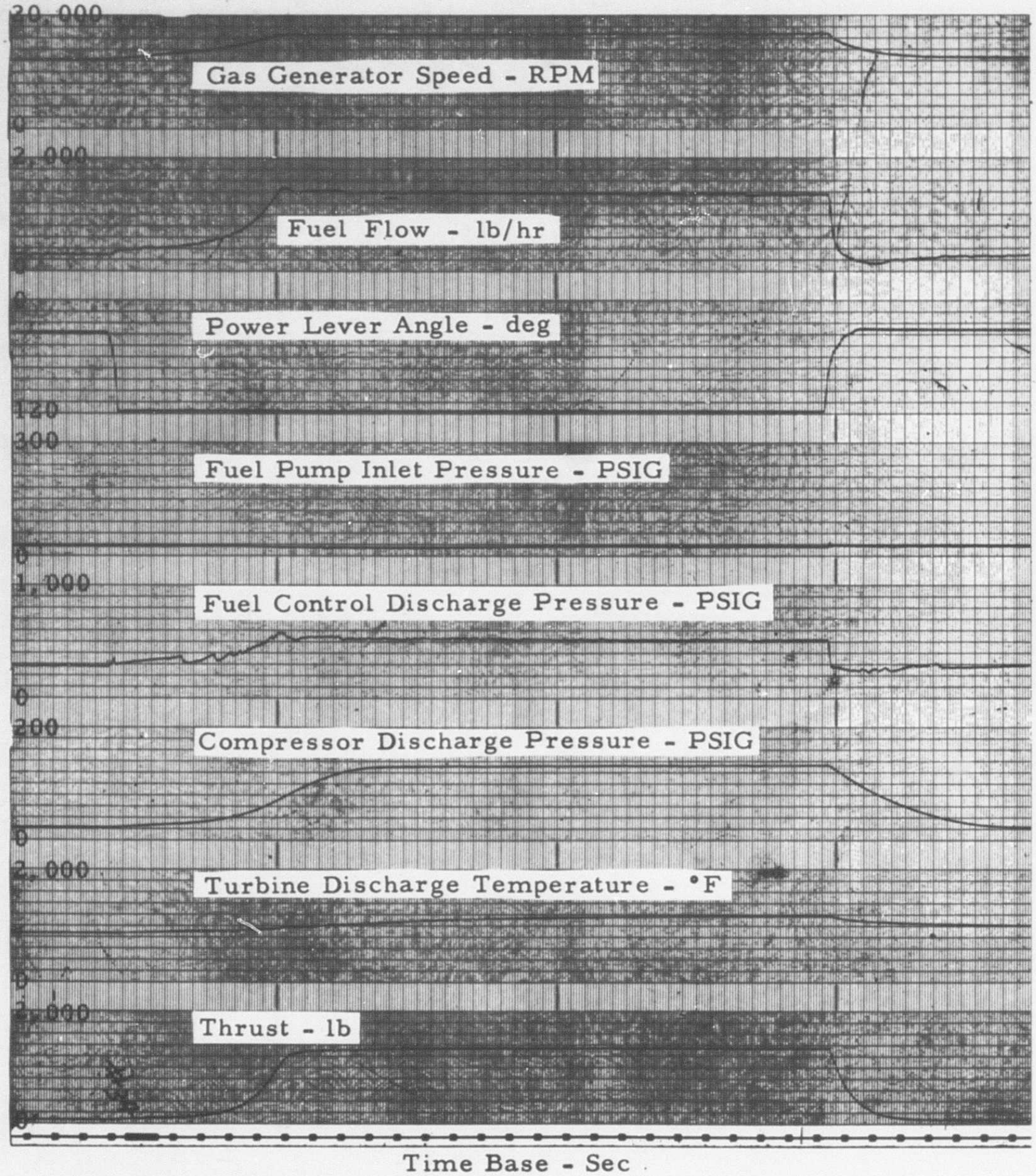

Figure 13. Burst to Maximum and Chop to Ground Idle (JD-1).

APPENDIX I

BENCH TEST OF FUEL CONTROL

The object of the control bench tests was to determine whether any control schedule deterioration occurred as a result of engine testing with JD-1.

The fuel control (Drawing #37D402077P107, S/N 40151) was bench tested to the General Electric M50T1675 S-1 acceptance test prior to engine test.

The bench tests were conducted with JP-4 referee as called for in the contract. The limits called for on the acceptance test apply to MIL-F-7024A Type II fuel. The results are shown in Figures 14 through 18. The points which appear out of limits in Figures 14 through 18 are due to the different specific gravities of JP-4 and MIL-F-7024A.

A $T_2 = 69^{\circ}F$ acceleration curve was also conducted with the fuel control operating on JD-1. The control operated satisfactorily on both JP-4 and JD-1.

The difference in W_f/P_3 for the steady-state results in Figures 14 through 16 is due to the changes in maximum and idle trim made during the engine test.

The $T_2 = 69^{\circ}F$ acceleration schedule (Figure 17) shows that the acceleration schedule was unaffected by the operation of JD-1. The schedule run on JD-1 and the final JP-4 schedule are almost identical with the initial JP-4 schedule.

The maximum flow, minimum flow, minimum ratio (Figure 18) shows that the control was unaffected by the engine test.

It can be concluded that the fuel control operated satisfactorily during the engine test and that the bench test did not reveal any deleterious effects.

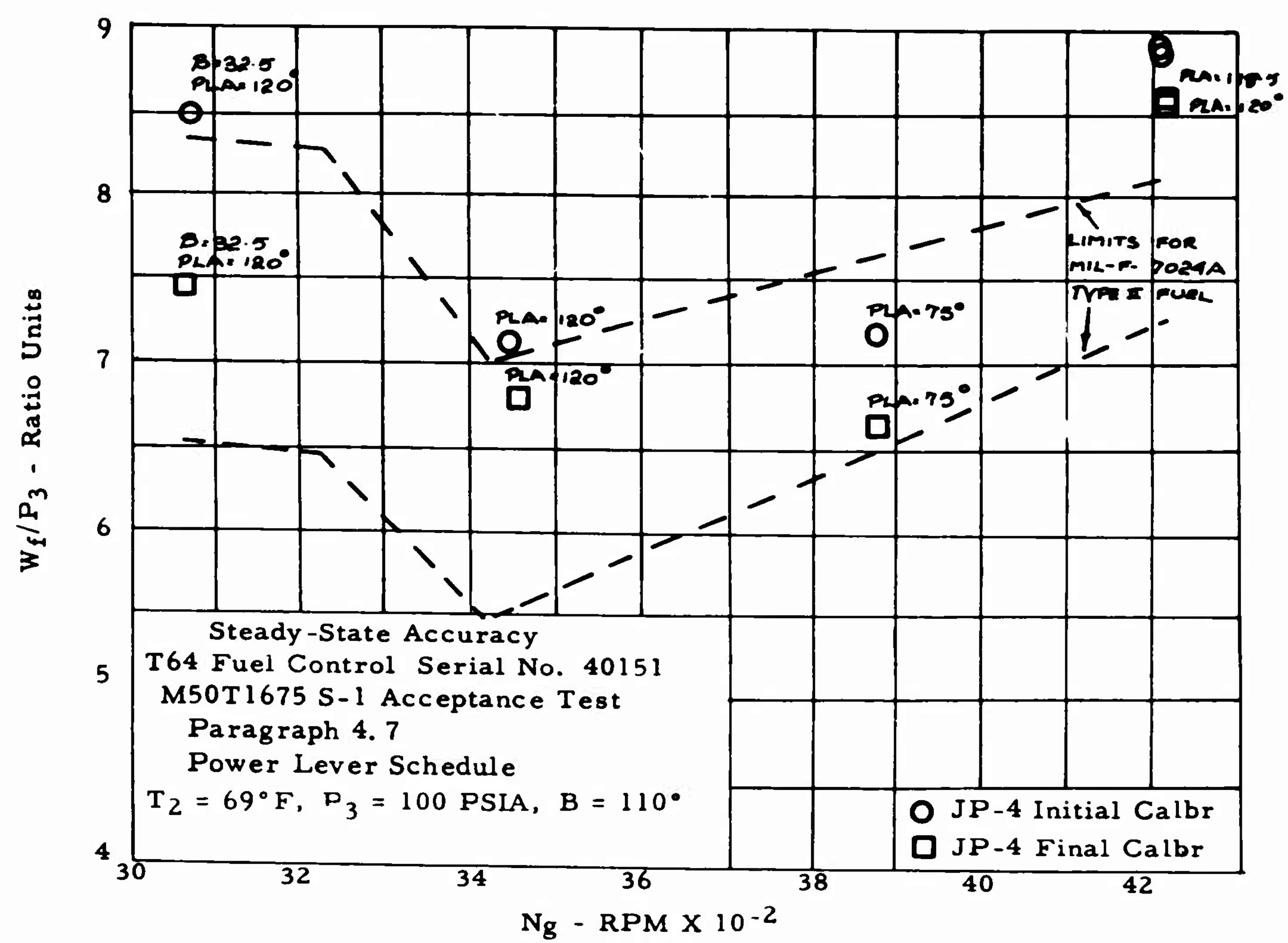

Figure 14. Fuel Control Power Lever Schedule Check.

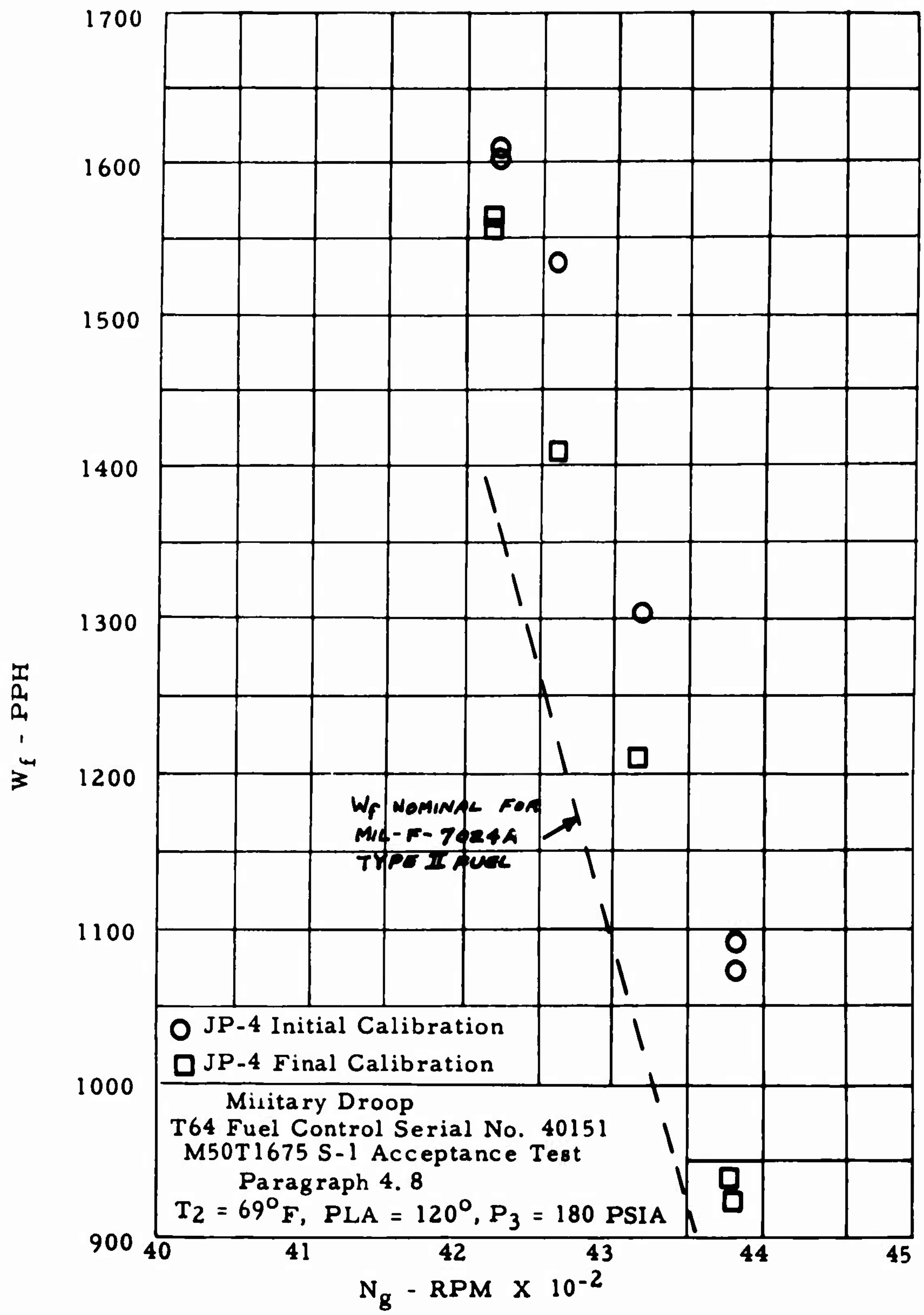

Figure 15. Fuel Control Military Droop Check.

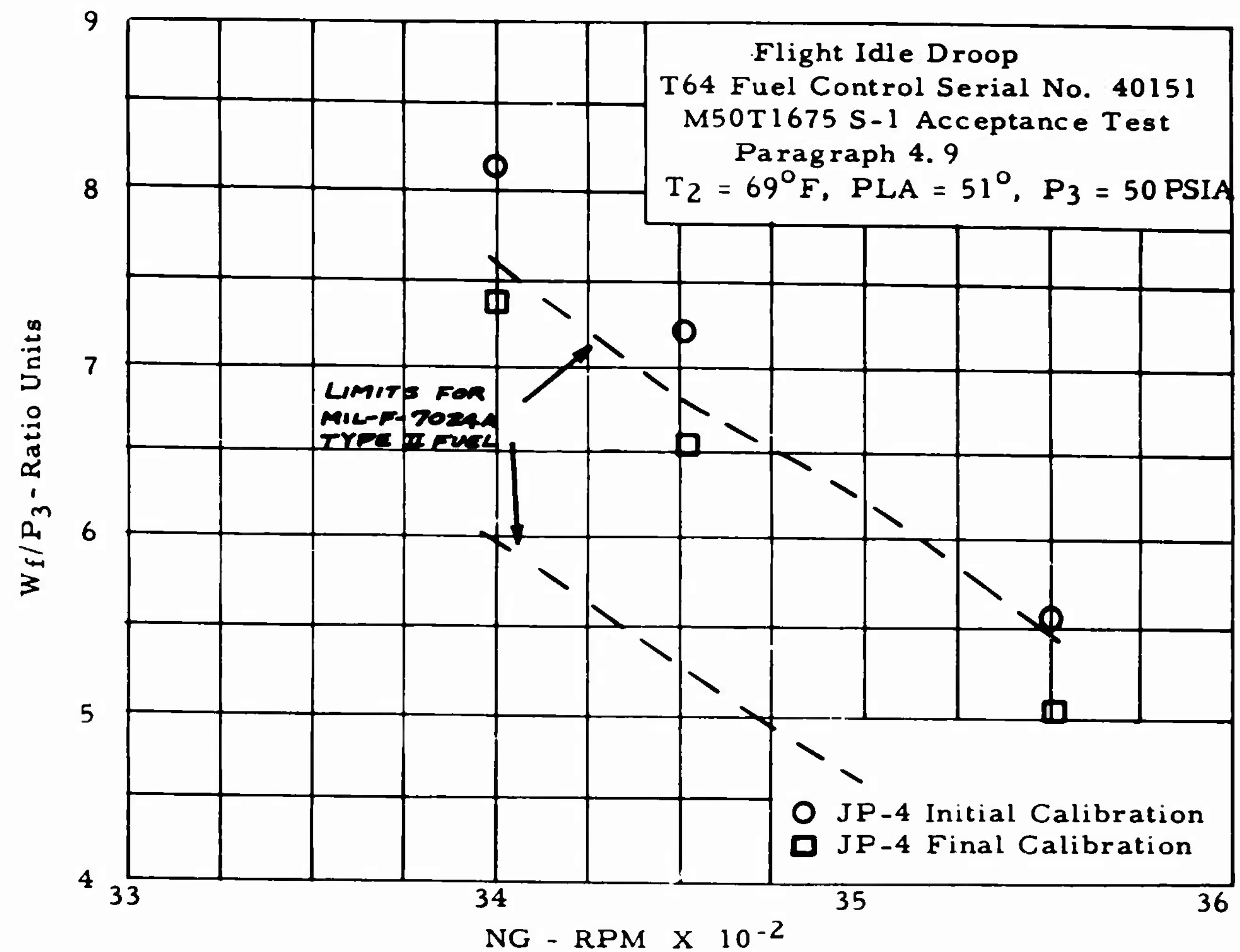

Figure 16. Fuel Control Flight Idle Droop Check.

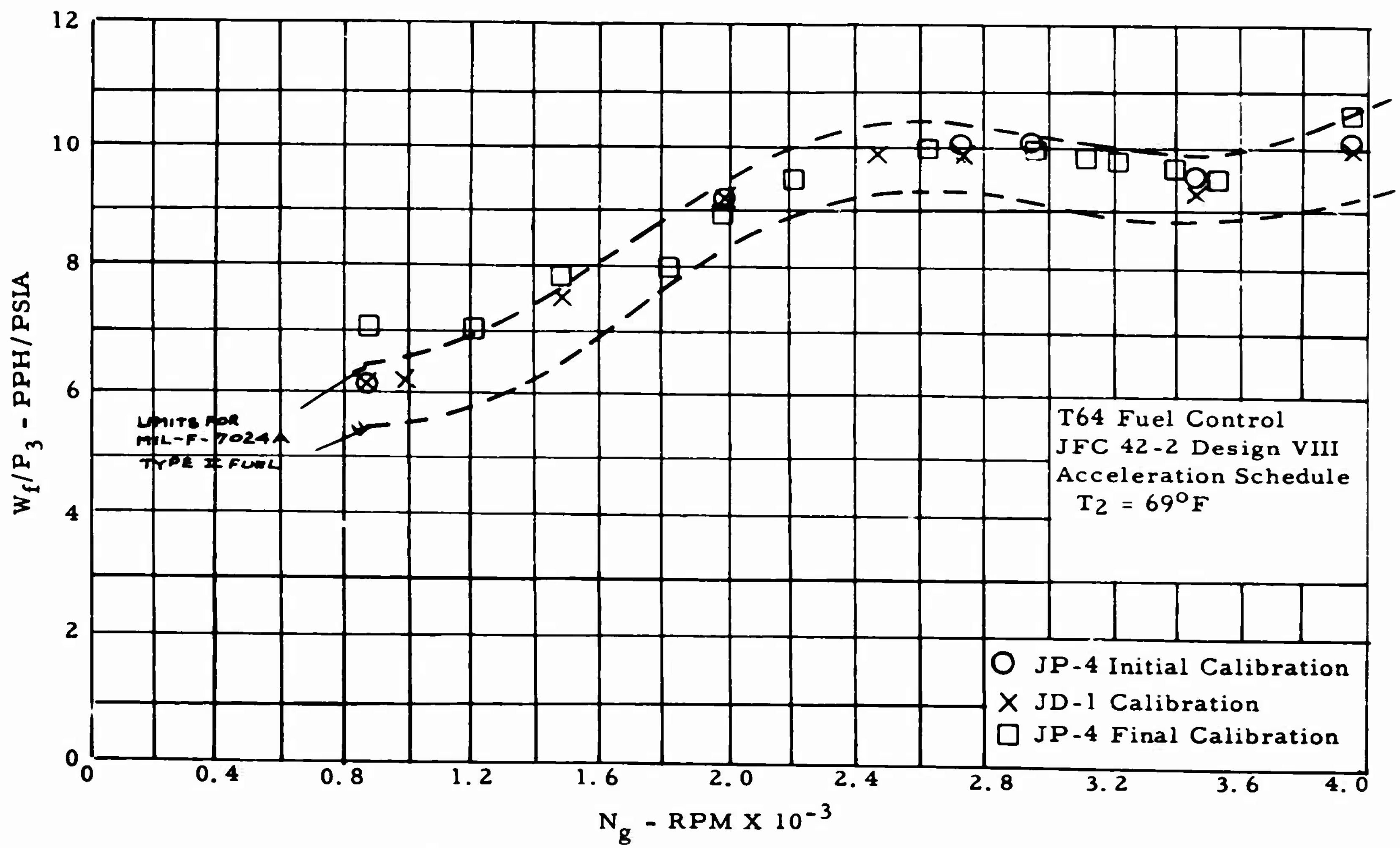

Figure 17. Fuel Control Acceleration Schedule (T_2 = 69°F).

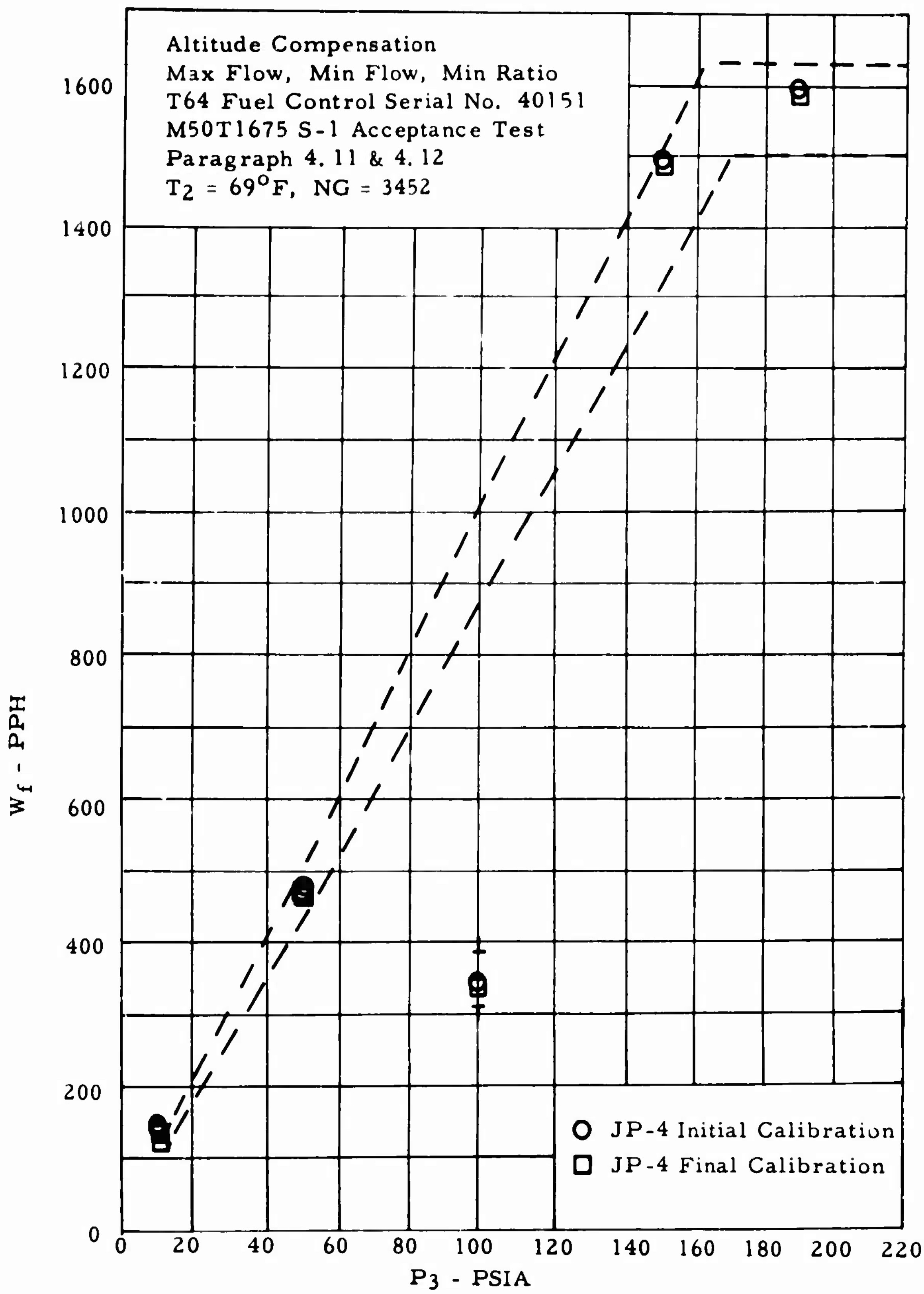

Figure 18. Fuel Control Altitude Compensation Check.

APPENDIX II

BENCH TEST OF FLOW DIVIDER

On completion of engine test, the flow divider was bench tested to General Electric bench test instruction 64AQC-37. The flow divider Drawing # 4001T83P02 S/N 166 met the bench test requirements on all conditions except the flow hysteresis check. The results of that check are below:

Secondary Fuel Flow PPH	Boost Pressure PSIG	Inlet Increasing	Pressure Decreasing	ΔP
50	70-85			
200		293	241	$\boxed{52}$
600		326	317	$\boxed{9}$
1000		456	385	$\boxed{71}$
1400		618	515	$\boxed{103}$
1600		792		

T64 development engines have, on occasions in the past, completed a 150-hour endurance test with a flow divider with a hysteresis ΔP of 60 psi. No engine has been tested with a ΔP of 103 psi.

During the safety fuel engine test, the flow divider hysteresis did not make itself apparent on engine operation. It is believed that the flow divider could operate for a longer period than the 3 hours before it would limit engine operation.

Further testing will be necessary before the period of trouble-free operation can be established.

APPENDIX III

BENCH TEST OF FUEL NOZZLES

The fuel nozzles were bench tested to General Electric bench test instruction T64AQC-14 before and after the engine test. The test consisted of a leakage test, a fuel flow test, and a spray quality test. The fuel nozzles met all the test requirements on the initial bench test.

The results of the final bench test indicated that none of the nozzles leaked but they all failed the spray quality test, the spray being streaky instead of homogeneous. The fuel flow results are tabulated below:

TABLE II

BENCH TEST RESULTS OF THE FUEL NOZZLES

Nozzle Conditions	P-200 S-0	P-0 S-200	P-500 S-500
	PPH	Fuel Flow PPH	PPH
Limits	10.6/12.5	82.5/99.0	148.4/166.4
Nozzle #			
1	11.2	65.1*	139.2*
2	11.25	88.5	145.0*
3	9.2*	69.65*	117.0*
4	7.25*	85.0	135.0*
5	11.15	86.0	141.5*
6	12.3	86.0	135.5*
7	6.45*	75.5*	134.0*
8	11.4	69.8*	134.5*
9	12.0	85.0	142.0*
10	11.0	85.0	139.5*
11	9.9*	84.0	137.0*
12	7.25*	85.5	134.0*

* Figures are outside the test request limits.

Although the nozzles did not meet the bench test requirements, no effect was observed on the engine operation during test.

PART 2. ALLISON, T-63

by
J. R. Lucas
Allison Division, General Motors
Indianapolis, Indiana
Contract DA 44-177-AMC-428(T)

OBJECTIVE

The purpose of this series of tests was to investigate the feasibility of burning an emulsion of JP-4 fuel in water in a T63-A-5A turbine engine. The testing was divided into two phases:

1. Bench testing of a T63 fuel system for the purpose of examining and comparing operation while delivering standard test fluid and emulsified JP-4.

2. Engine testing of a T63-A-5 free turbine engine for the purpose of comparing operation and performance while burning JP-4 and emulsified JP-4 fuels.

The series of tests also attempted to illuminate any necessary areas of further engineering study in order to allow engine compatibility with emulsified fuels.

CONCLUSIONS

It is feasible to operate a gas turbine engine, specifically the T63-A-5, on an emulsion of JP-4 fuel in water. Satisfactory engine operation was obtained with the following conditions or exceptions:

1. The emulsified fuel as tested corrodes materials susceptible to rust or attack by free water. Rust particles carried in the fuel are abrasive to fuel system components and, to a lesser degree, interior engine components in the gas path. Sufficient quantities of rust were present to clog fuel system screens and filters in a few hours of operation.

2. The metered fuel flow by weight was less through a given system for emulsion than for liquid, resulting in lean fuel schedules when liquid JP-4 control settings were retained and emulsion flowed.

3. There was no detectable power sacrifice involved in using emulsified fuel in sufficient quantities. Satisfactory stability was also achieved.

4. The standard engine fuel system can be used with emulsified fuel with relatively minor adjustments and modifications for standard sea level conditions.

5. The bulk of the fuel remains in the emulsified state through the fuel system and past the point of atomization in the nozzle, even in 100°F. ambient conditions.

RECOMMENDATIONS

In view of the results of this test and the exceptional safety value of a fuel in this or similar form, further engineering study of a standardized or specified safety fuel, as soon as it is available, is warranted. The test results indicate that if the corrosive nature of the emulsified fuel can be corrected, only minor engine modifications would be necessary to achieve entirely satisfactory engine operation.

Development and testing of combustion and fuel system components and transport, storage, and filtration techniques seem to be warranted. The majority of engine malfunctions in this test, however, can be credited directly or indirectly to the corrosive nature of the emulsified fuel.

DISCUSSION

The particular emulsion employed in this test is a dispersion of fuel in water. Physically, the emulsion is a collection of minute drops of JP-4 with thin coats or balloons of water around them. The emulsifying agent, Westco MFE-10, in this case, allows these balloons or bags of water to be formed with tiny drops of fuel inside. The fuel is then known as the interior phase and the water as the exterior phase.

The safety aspect of this fuel results primarily from the fact that the liquid JP-4 has no surface exposed to air; it is all contained in a skin of water. This causes the rate of vaporization to be very much lower than that of free liquid fuel. In an airplane crash, this implies that, even if a fuel tank has burst, a vapor cloud of fuel and the inevitable fireball will not form. Rather, a slow, controlled burning takes place on the surface of the emulsion. It is important to note that the chemical composition of the fuel has not been changed, only the physical state.

A secondary consideration is the greatly (approximately $\times 10^6$) increased viscosity of emulsified fuel. This implies that the emulsified fuel may not splash or disperse as readily as the liquid. Fuel system leaks would be readily detectable because the emulsion will extrude like toothpaste However, the much higher viscosity naturally affects flow properties. The emulsion moves in discreet "plug flow" - a completely laminar plug moving on a very thin boundary layer of liquid fuel.

In the course of testing, two different blends of emulsion were prepared. The bench test was run by flowing a mixture of 96% JP-4, 3.5% water, and 0.5% emulsifying agent by volume. Based on test results from another company, a blend of 96.85% JP-4, 2.5% water, and 0.65% emulsifying agent by volume was used in engine testing as suggested by the Western Company representative. The Material Services Lab Report (AW.0000-054) covers analysis of the blend used for bench testing and reports a low temperature tolerance of -10°F. The Western Company representatives mentioned a figure of -40°F., but at this point in development, batch-to-batch variation is high. The change in blend between bench and engine, however, was not sufficient to affect pressures, flows, or spray angles recorded. Essentially, the change affected the amount of free fuel in the Western Company emulsion supply drum.

BENCH TESTING

Bench testing was accomplished in cubical 56 in the Fuel Components Lab at Allison Plant 2. An A-5A fuel pump (P/N 6854292), A-5 fuel control (P/N 6840339), A-5 fuel nozzle (P/N EX70363), and later an A-5 fuel

nozzle (P/N 6846345) were employed. All components were flow checked prior to the beginning of the test.

The complete engine fuel system was set up in the following manner. The fuel pump and fuel control were mounted on the driven pads in the test cell in the usual manner. Regulated shop air was connected to the P_c port of the fuel control, the pump and control outlets were plumbed together, and test fluid was supplied to the pump.

The fuel nozzle was mounted in a fixture in the dome of a nozzle spray visualization rig. This rig consisted of a 35-gallon stainless steel catch drum and a steel top or dome. The dome had a viewing port and two 100-watt lamps spaced approximately 120° apart. In this manner, the nozzle spray was back-lighted and could be photographed. The outlet of the control was then connected to the nozzle inlet through a 1/8-inch Potter turbine flowmeter. The flowmeter readout was on an EPUT event counter through a 10 × amplifier. The test bench provides a readout of fuel control r.p.m. on a second EPUT. Pressures were read at appropriate points in the fuel system on the stand pressure gauges. The bench test setup is shown in Figure 19. A photograph of the test set is shown in Figure 20.

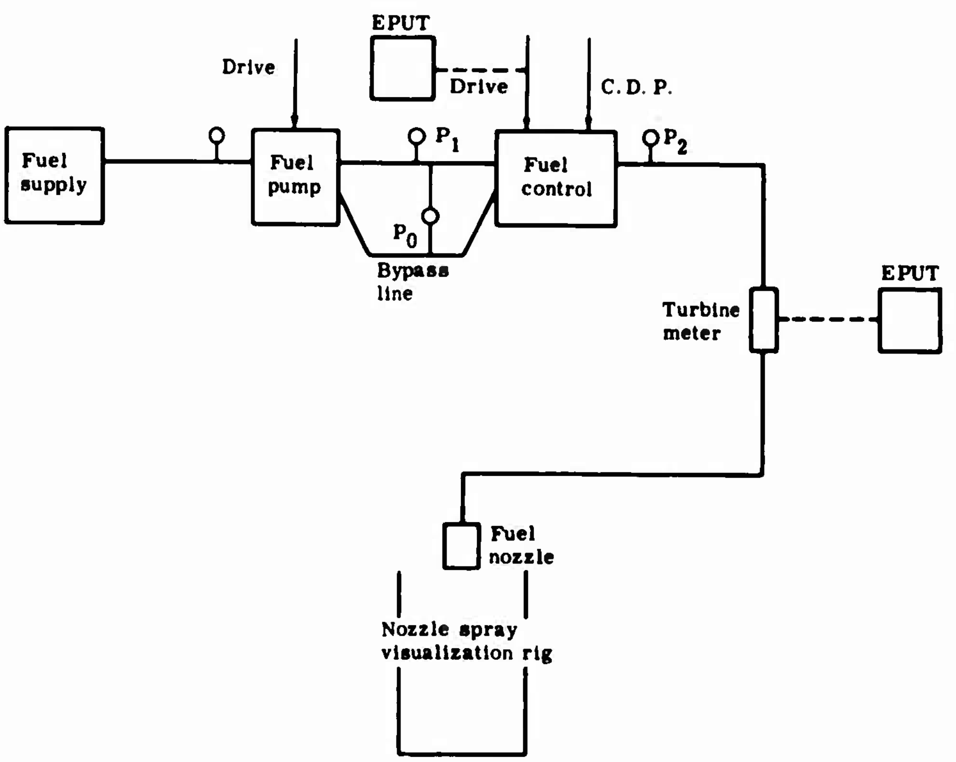

Figure 19. Block diagram showing bench test setup of engine fuel system.

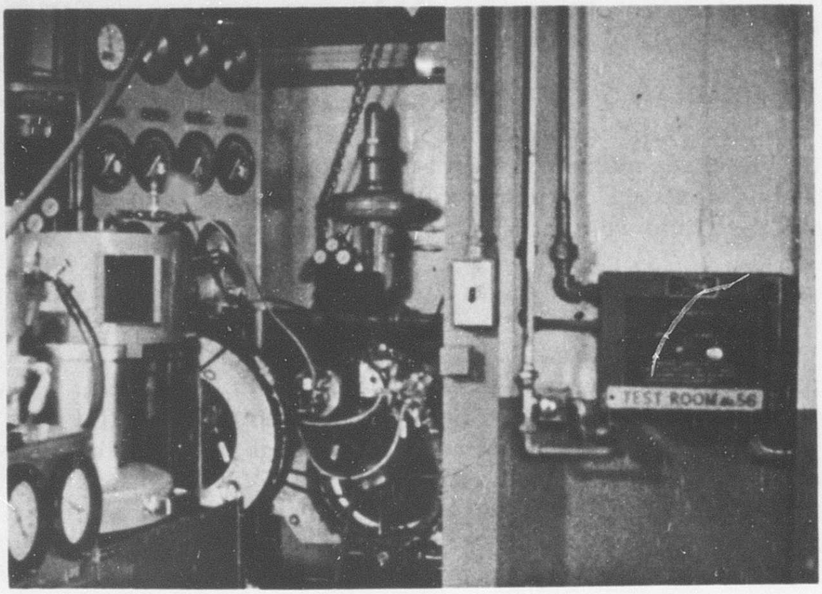

Figure 20. Bench test setup of engine fuel system.

The first series of tests was run by flowing test fluid MIL-F-7024-IIA, a fluid very similar to JP-4 in viscosity and density, but with much less flammability. Ten points on the fuel control acceleration schedule were chosen from the standard E.D.S. check, and test conditions were set in the same order throughout the test: (1) C.D.P. (P_c), (2) speed, and (3) fuel supply. Finally, the nozzle spray at each test point was observed and photographed with a Polaroid camera, and nozzle spray angles were measured from the Polaroid snapshots. During the first test sequence, the A-5 fuel nozzle (P/N EX70363, S/N AGH-195) was used, and the pump filter was retained.

When emulsified JP-4 was available, the stand test fluid connection was removed from the fuel pump and the emulsion supply line from the Westco rig was connected directly to the pump. The Westco rig (Figure 21), in which both the JP-4 was emulsified and the emulsion was pumped or supplied, was capable of supplying emulsion to the pump from 0 to approximately 80 p.s.i.g. For fuel supply the rig employed a single-piston air-driven pump and follower plate suspended in the 55-gallon drum containing the emulsion. The pump was the same type used to pump grease and heavy oil for grease guns. Based on the experience of the Westco representative, a pump supply pressure of approximately 30 p.s.i.g. was chosen.

Figure 21. Westco emulsified fuel mixing and supply rig during fuel mixing.

After the pump and control were run long enough to flush the test fluid thoroughly from the system, the same test sequence was repeated by flowing emulsified JP-4. The pump filter pressure drop had been instrumented, and the pressure readings were high enough to indicate that the filter bypass valve was open. Instabilities in nozzle flow, spray angle, and system pressures were noted, and the turbine meter would not perform satisfactorily.

As a result of this first run, the pump filter was removed. It was found that the paper filter element had passed emulsion, but the resultant pressure drop was much higher than with liquid. A 3/16-inch turbine flowmeter was also installed, and the screen filter incorporated in the fuel nozzle was removed in an effort to derive intelligent fuel flow data and to reduce the flow instability.

A short run at several test points demonstrated a very poor spray quality with this configuration, particularly at low nozzle pressure and low flow. The turbine meter readout remained inconsistent and unsatisfactory, even at high flow. It was decided to replace the nozzle screen with the thought that it aided in shearing and breaking up the emulsion and thereby improving spray quality. Another short run at several test points showed an improved nozzle spray, in the low flow and pressure range especially, and a reduction in pulsation and instability.

With the thought that the pulsations may be caused by the supply rig pump and as a protection against system contamination, a 200-mesh wire screen canister filter was fabricated and inserted in the fuel supply line between the supply rig and the pump. The test sequence was again run, with pulsations and nozzle spray instability observed only to a small degree and in the low flow range. Flow rate was measured by catching the nozzle spray in a can for a known length of time and weighing the flow.

After shutdown, however, the nozzle continued to drip and spurt for some time in a manner that indicated that the fuel was compressible to some degree. This was judged to be due to entrained air and was later confirmed by lab test and further testing. The ensuing startup produced the same fluctuating nozzle spray angle and poor spray quality demonstrated before, and corrosion and rust were noted on the nozzle air shroud and nozzle fixture. With the thought that the old nozzle may have been contaminated, it was removed, but successfully resisted all attempts to disassemble it. This, however, was not necessarily the fault of the emulsified fuel flowed through it. A new nozzle (P/N 6846345, S/N AGM 432) was installed in the system, and, as the turbine meter had proved unacceptable, it was removed.

For the final test sequence with emulsified fuel, the fuel system configuration consisted of the Westco supply rig, the 200-mesh filter, the fuel pump less its filter, the fuel control, and the new nozzle. This was defined as the engine test configuration. The same pressures were read as before; while the test sequence was repeated, the nozzle spray was again photographed to determine nozzle spray angles. Flow was measured by weight versus time as in the preceding sequence.

Finally, the Westco supply rig was removed, the pump filter was replaced, the original turbine meter was replaced in the nozzle line, and test fluid was supplied to the pump. With this configuration the test sequence was repeated flowing test fluid. After completion, the pump filter was removed; and the pump, the control, and the new nozzle (S/N AGM 432) were mounted on the engine for engine test.

ENGINE TESTING

Engine testing was accomplished in the altitude tank at Allison, Plant 2. A T63-A-5 engine, S/N W-40, buildup 12, was used. The fuel system configuration employed was that described in the last emulsified fuel bench test sequence: the A-5A pump less incorporated filter, the A-5 fuel control, and the A-5A fuel nozzle P/N 6846345, S/N AGM 432. The 200-mesh canister filter was not incorporated at this point in the test.

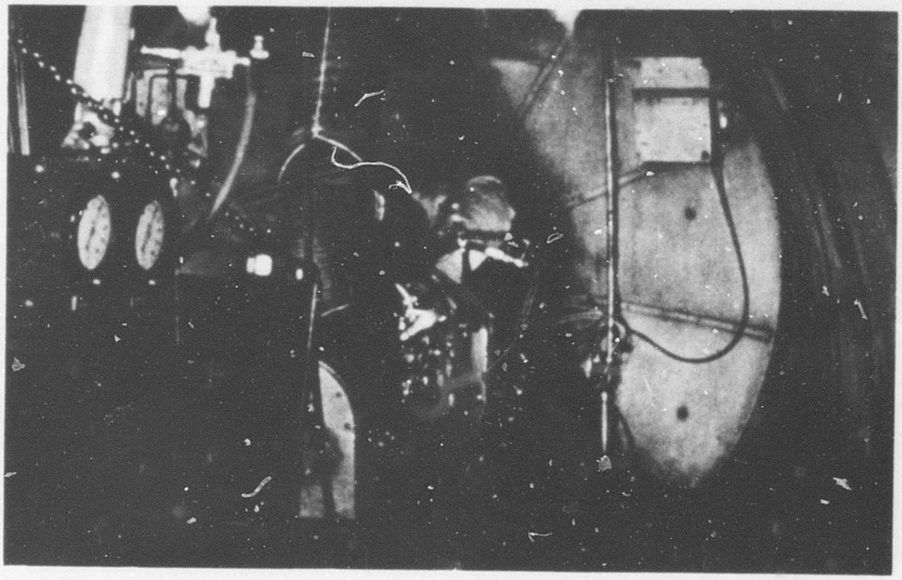

Figure 22. Engine test setup in altitude tank.

The engine was installed in the altitude tank driving a water brake for power absorption and a flywheel for drive train inertia effect. This test setup is shown in Figure 22. Test stand instrumentation was provided as available to measure the normal engine parameters: rotor speeds; torquemeter oil pressures; inlet, outlet, and internal engine pressures and temperatures; lube and fuel system pressures and temperatures; and engine vibration. A 1000-pound rated weight-measuring load cell was suspended from the ceiling of the altitude tank, and a full drum of JP-4 was suspended from it as the fuel supply for the engine. The following parameters were recorded on an Offner Recorder: gas producer speed (N_1), output speed (N_2), engine torquemeter oil pressure, turbine outlet temperature, fuel nozzle inlet pressure, and fuel supply weight as indicated by the load cell. A boost pump delivered fuel from the supply drum to the engine fuel pump.

In this configuration the engine was performance-calibrated at ground idle and approximately 78%, 86%, 92% rated N_1 speed, and takeoff temperature with 100% N_2 speed. (These 5 steady-state points were used throughout the test.) Fuel flow was determined by the change in fuel supply weight with time. After steady-state operation, the engine was accelerated and decelerated a number of times between ground idle and approximate takeoff temperature to establish transient performance while burning liquid JP-4. This test sequence established a base line for comparison of liquid JP-4 and emulsified JP-4 burning.

The drum of JP-4 and the boost pump were then removed from the tank. The emulsified fuel supply rig was suspended from the load cell, and the 200-mesh canister filter was incorporated in the fuel supply line to the engine. Shop air was supplied to the emulsified fuel supply rig, but the liquid JP-4 remaining in the engine fuel system after the last shutdown was not bled. This allowed the engine to fireup on liquid JP-4 with emulsion pushing the liquid through the system.

The first two starts resulted in normal light-off and acceleration on JP-4 fuel, but there was loss of fire when the emulsion reached the fuel nozzle. The fuel system was then flushed and primed with JP-4, and the emulsion supply was reconnected to duplicate the conditions of the first start. The fuel nozzle and igniter were removed from the engine, but no emulsion was observed in the combustor. Again the engine started successfully, but lost fire when the emulsion reached the nozzle.

The fuel system was again flushed and primed with JP-4 as before. The P_c line to the fuel control was broken and capped, and regulated shop air was supplied to the P_c port of the fuel control. This allowed a false input to be given to the fuel control so that it could be made to supply more fuel than it would for a given engine-supplied input. This was done in light of the bench test results, which indicated a lean fuel schedule when emulsified JP-4 was flowed. Engine speed control was still provided by the governor function of the control, however.

In this configuration, the engine successfully started and sustained fire after the emulsion reached the nozzle and began to be burned. The same steady-state points were run for this and the remainder of the test as had been run for the liquid JP-4 performance calibration. At this point, the false P_c signal was removed and the fuel control metering schedule was enriched by an orifice adjustment. The orifice adjustment on the fuel control was moved out or enriched approximately 1/8 turn without disturbing any other adjustments or settings. A series of successful starts and a check run were made on liquid JP-4; but, due to the fact that the control was running quite a bit richer, approximately 1 inch of mercury ram was necessary to prevent an overtemperature start on liquid fuel.

The Westco supply rig was again suspended from the load cell, and the engine started successfully on liquid fuel and sustained fire during the transition from liquid to emulsion. The steady-state points were again repeated. During the course of further running, the engine shut down, but it was successfully restarted on emulsion alone several times with no liquid fuel priming. The longest ambient soak before starting was approximately 2 hours. Smoke issued from the engine exhaust, and slight afterfires were present

for several shutdowns; occasionally, a small explosion was heard in the combustion section on fire-up. This was undoubtedly due to the fuel nozzle leaking fuel during and after shutdown, as observed during bench testing.

The engine was started and run on steady-state points and transients until approximately 4 hours of emulsified fuel running had been accumulated. During this time several malfunctions occurred, but none were caused by faulty engine operation on the emulsion. After this point, however, difficulty was encountered intermittently with what seemed to be control "sticking" or "hang-up" and difficult fire-ups with both liquid and emulsified fuel. At the end of the shift, the engine was operated on liquid JP-4, and the liquid remained in the fuel system over a 3-day holiday weekend. This was done to prevent possible corrosion not attributable to actual engine operation.

At the beginning of the shift after the weekend, the liquid JP-4 was flushed from the system and emulsified fuel was supplied to the engine for a cold start attempt. The engine would not fire on emulsion. After flushing and priming with liquid JP-4, the engine would fire up but would not sustain fire during the transition to emulsion. The engine was then run at three calibration points on liquid fuel alone. The control system again gave some difficulty symptomatic of sticking of internal parts.

After the engine had been warmed thoroughly during the abridged calibration, the engine was shut down, the emulsion supply was connected to the engine, and the engine was refired. Startup on liquid and transition to emulsion burning were accomplished satisfactorily on the hot engine, and the same five steady-state points were run again. At the takeoff temperature point, one exhaust stack became disconnected, but no flame or other abnormal running condition was visible in the exhaust collector. The engine was shut down.

While the exhaust system was being repaired, the Westco rig was removed. The remaining emulsion showed discoloration and partial breakdown after its manufacture before the weekend. It was summarily disposed of and a new supply prepared.

During this time, the fuel nozzle was removed from the engine. Disassembly and inspection showed the nozzle screen to be nearly covered with rust particles, what appeared to be white fibers, and paint of the type coating the inside of the drum in the emulsion supply rig. The white fiber-like material was actually polymer strings created by the emulsifier. The nozzle tip showed normal carbon buildup, but some abrasive wear was apparent in the nozzle passages. The nozzle was cleaned and subjected to an E. D. S. check at this time and then reassembled on the engine.

When the emulsified fuel was available, the supply rig was suspended in the tank and reconnected to the engine. After an ambient soak of approximately 4 hours, the engine started satisfactorily on emulsion only. After a warm-up period, transients between ground idle and takeoff were again performed. Finally, the engine was run at takeoff for approximately 15 minutes, and then ground idle for the required 2 minutes. This concluded the engine running on emulsified JP-4; approximately 6.5 hours of total running time on emulsion were completed.

After removal of the engine from the altitude tank, the fuel pump and fuel control were returned to bench test for post-test calibration. The engine was returned to Plant 8 for partial teardown and inspection.

RESULTS

For ease of explanation, the two phases of the Emulsified Fuel Comparison Test will be dealt with separately, i.e., bench test and engine test. The most critical problem area indicated by both phases of this test was the corrosive nature of the fuel. This one undesirable fuel property resulted in the majority of the subsequent test difficulties, but perhaps could be corrected by a small percentage of some additive such as sodium bromide.

BENCH TESTING

Taking the components of the fuel system in order, the fuel pump will be discussed first. As mentioned in the procedure section, the 10-micron pleated-paper filter incorporated in the fuel pump will filter and pass emulsified JP-4 but with a pressure drop sufficient to keep the filter bypass valve open. Tests outside Allison have resulted in the collapsing of both paper filters and thin metal screens with normal fuel system pressures when a large quantity of contamination is present in the emulsified fuel being delivered.

Test instrumentation did not monitor pump speed, but the test bench drives the pump in the same ratio to fuel control speed as the engine drive train. As mentioned previously, the pump outlet saw essentially the same system, if not the same back pressures, for the duration of the test. With reference to Figure 23, the pump appeared to contribute a slightly smaller pressure increase at low and high speed on emulsified as compared to liquid JP-4. Otherwise, pump operation was completely satisfactory during the test. The post-test E. D. S. check showed the pump to have deteriorated beyond acceptable limits, however, and the pump flow was just below the lower limit.

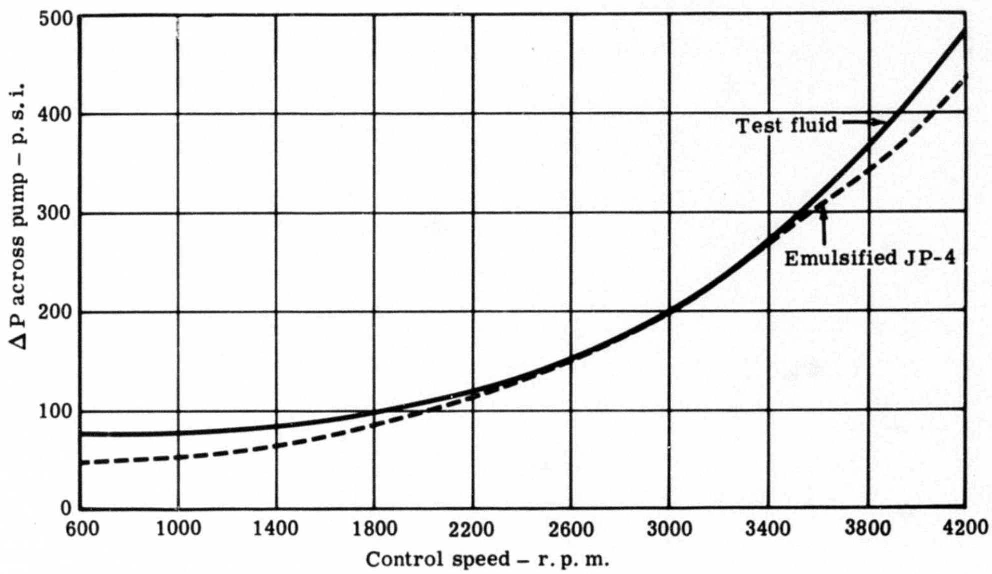

Figure 23. Increase in fuel pressure supplied by engine-driven fuel pump versus speed while flowing test fluid and emulsified JP-4.

Figure 24 shows that, for the same settings, the fuel control flows a leaner schedule on emulsified than on liquid JP-4. In general, the control tends to meter in the same fashion, and the liquid and emulsified plots are roughly parallel. The fuel control also seems to have depreciated in flow during the test. The orifice adjustment made on the engine test stand should have produced a higher flow rate than the post-test calibration indicates. This may also indicate that with some enrichment in the start and acceleration to idle range, the engine could be made to perform adequately as it did towards the end of the test with a control set to the high limit of the E. D. S. As this test was only intended to indicate feasibility, no tailoring of fuel control characteristics was attempted.

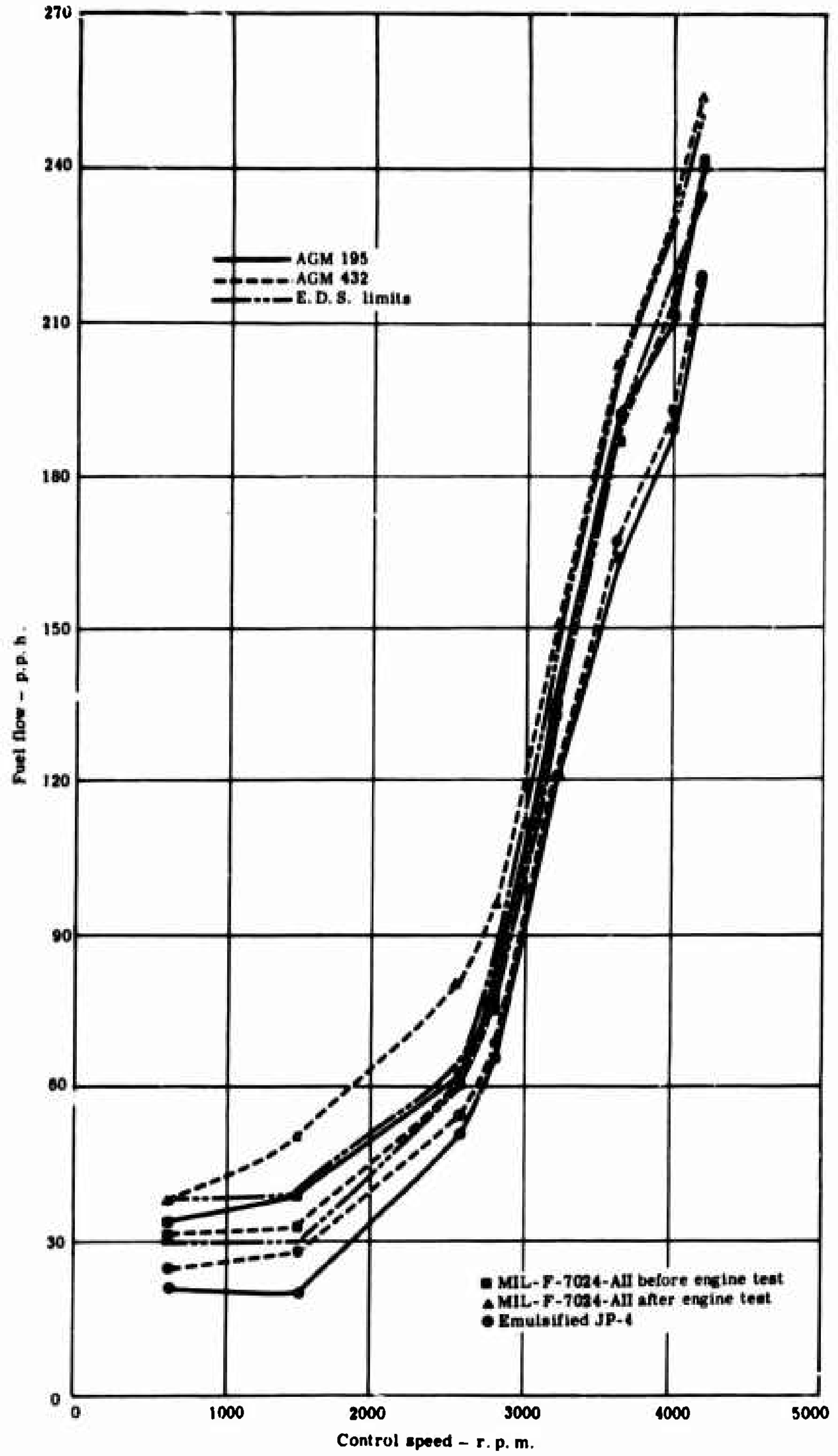

Figure 24. Fuel flow metered by fuel control versus control speed while flowing test fluid and emulsified JP-4.

The fuel nozzle was affected to the greatest extent of any of the fuel system components. As mentioned previously, a nozzle spray angle fluctuation of 10 to 20 degrees and a very poor spray quality were obtained with the older nozzle (S/N AGH 195) when emulsion was flowed. The spray cone appeared alternately to adhere to the air shroud and then to separate. This was perhaps due to a surface tension effect between the fuel spray and the wetted shroud. The problem was corrected for the most part by the substitution of the new nozzle (S/N AGM 432), but a spray angle fluctuation of some 5 degrees was still present at low flows. Figure 25 is not very conclusive, but it does indicate that the nozzle spray angle when flowing emulsion is wider at low pressures and narrower at high pressures than when flowing liquid JP-4. Also indicated is the depreciation of the spray angle after engine test. The nozzle remains within acceptable limits, however, and the effect is only slight.

Figure 26 indicates that the flowing of emulsion causes fuel nozzles to run lean also. The effect on engine operation is to create higher pressure levels throughout the fuel system. Depreciation with emulsion use is evident here as well as shown by the essentially post-test calibration of the nozzle. Not presented in chart form is the fact that the spray pattern of the nozzle was poor and beyond E. D. S. limits after operation with emulsion. This indicates that wear in the nozzle passages was significant after passing emulsion for less than 10 hours of operation. The wear was most likely due to small particles of entrained rust in the fuel which acted as an abrasive.

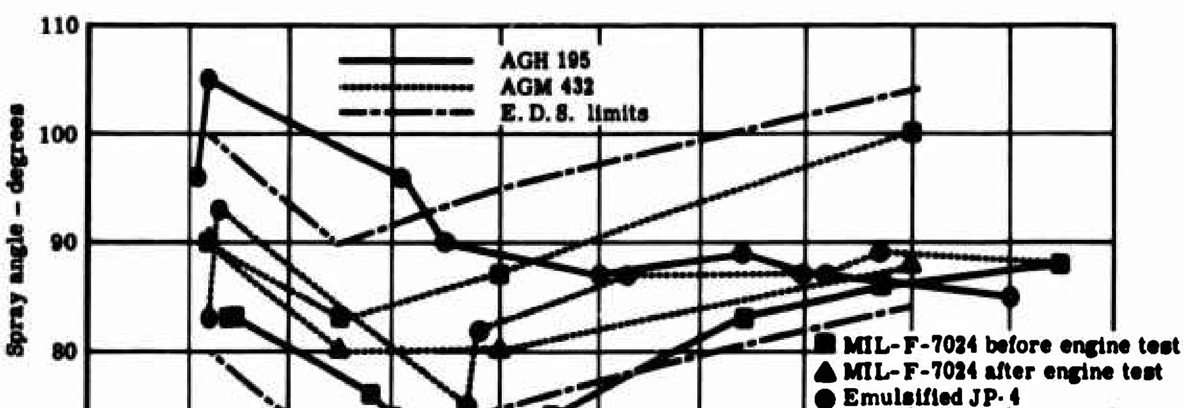

Figure 25. Fuel nozzle spray angle versus inlet pressure while flowing test fluid and emulsified JP-4.

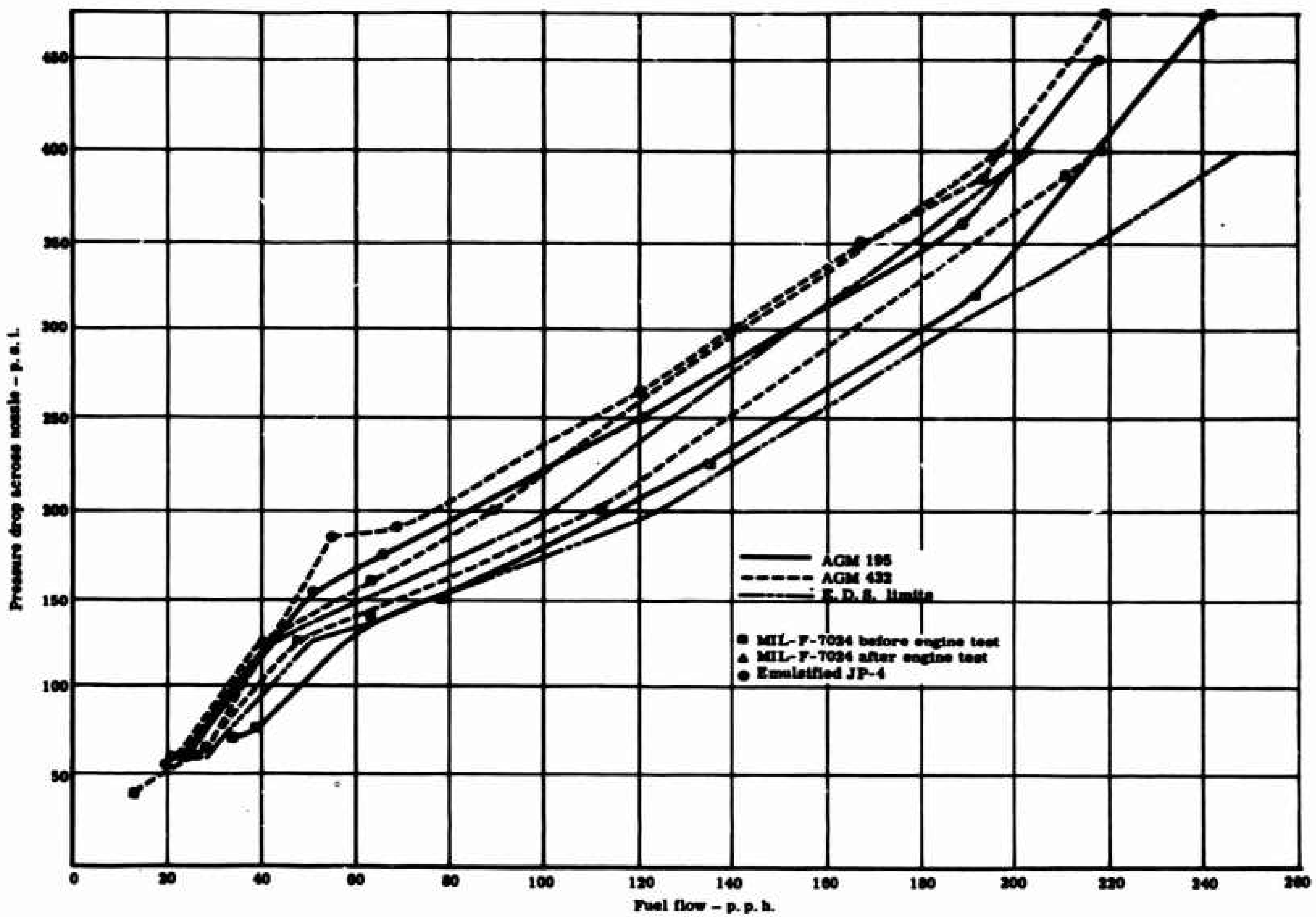

Figure 26. Fuel nozzle flow versus pressure drop while flowing test fluid and emulsified JP-4.

Teardown of the fuel control was necessary to remove all the emulsion from the passages, even though the control had been flushed with liquid fuel after removal from the engine. The only rust evident was on the cutoff valve. Considerable rust was found in and on the outside of the fuel nozzle, as mentioned previously. Partial teardown of the fuel pump also disclosed rust on the steel parts; the pump drive shafts and the end plates were removed and found to be rusted and pitted, respectively.

Besides the compressible nature of the fuel, due to entrained air, bench testing revealed that the emulsion was atomized as an emulsion and that significant breakdown did not take place after spraying. Lab testing and the testimony of the Westco representative indicated that the emulsion will break down and return to the liquid phase between 100 and 200°F., depending on the container material. This may indicate that an unsuccessful light-off on a cold engine would result in a mass of nondraining emulsion remaining in the burner can. Enough residual heat should be present in a warm or hot engine to liquify any unburned emulsion and allow it to drain from the burner as a liquid, but cold start attempts are a potential safety hazard. Photographs of the nozzle spray of the two fuels at take-off flow conditions are shown in Figures 27 and 28.

ENGINE TESTING

The results of the engine performance calibrations are contained in Figures 29, 30, and 31. The emulsion was prepared from the same batch of JP-4 that the preliminary liquid fuel base line was run on.

From a performance standpoint, the only effect of the emulsified fuel appears to be a slightly higher fuel flow and specific fuel consumption which can be explained by the fact that 2.5% of the fuel weight is inactive water. The emulsifying agent is organic and has some heating value. A second loss results from the fact that the thin skin of water surrounding each droplet of fuel must be broken away by shear or heat before the fuel inside is available to be burned. Within the accuracy of this test, these two considerations account for the total increase in fuel consumption.

Figures 32 through 37 are reproduced sections of Offner Recorder tape following the plots. They allow comparison between transient conditions burning liquid and emulsion. Figures 38, 39, and 40 are typical of the behavior of the same measured parameters during steady-state operation.

The first comparison is a fire-up on the two fuel forms. The fire-up on liquid shown here occurred after the fuel control orifice was adjusted. The fire-up on emulsion occurred with the system totally filled with emulsion. There were four main points of difference between the two fuels. The time to stabilize N_1 generally took two to six seconds longer with emulsion.

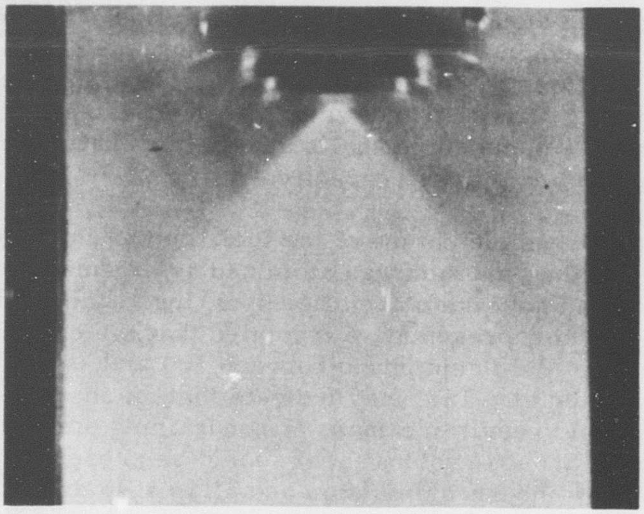

Figure 27. Engine fuel nozzle spray flowing liquid JP-4 at takeoff conditions, approximately 240 p. p. h.

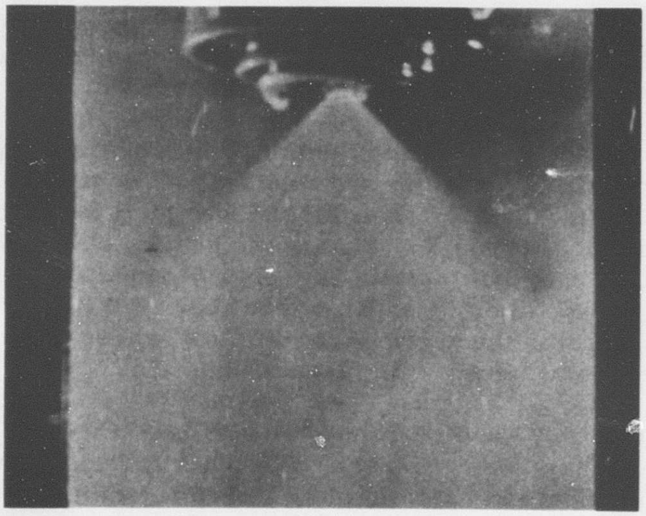

Figure 28. Engine fuel nozzle spray flowing emulsified JP-4 at takeoff conditions, approximately 220 p. p. h.

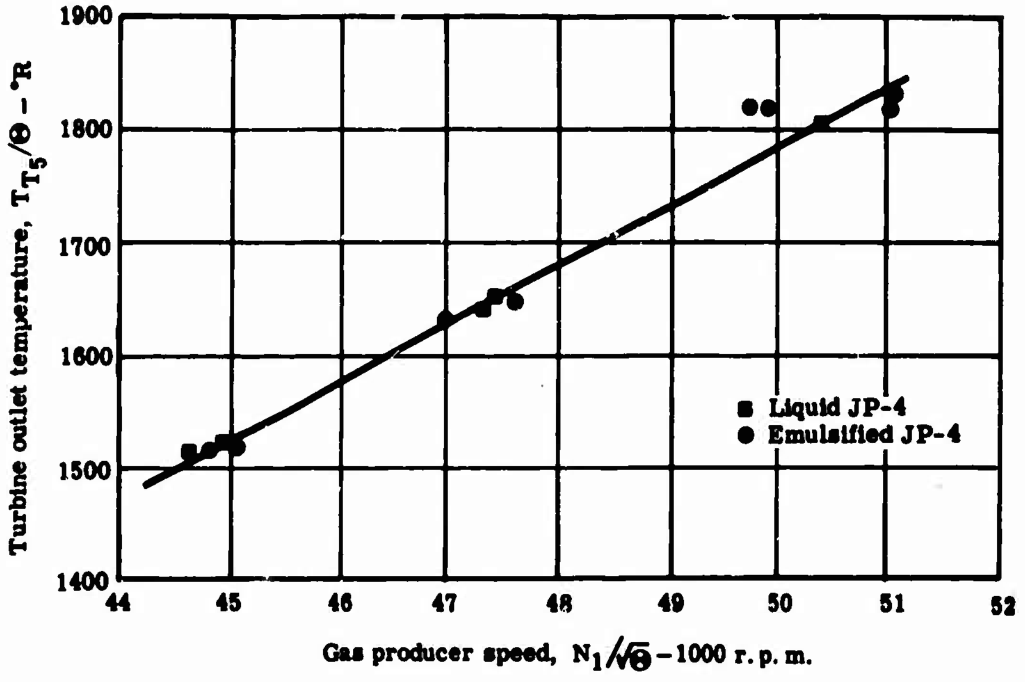

Figure 29. Turbine outlet temperature versus gas producer r.p.m. burning liquid and emulsified JP-4.

Likewise, the peak T.O.T. was generally the same or slightly lower. Emulsion starts also resulted in a lower nozzle pressure than did liquid starts, but the pressure fluctuations were sometimes half again as large as those with liquid in the system. All these effects could be accounted for by either the decreased heat release per pound of emulsified fuel or the compressibility factor.

Figures 34 and 35 allow a rough comparison of rapid accelerations on the two fuel types. Again it took slightly longer when using emulsion, but the variety of conditions did not allow a specific time band to be estimated. The air in the fuel causes the typical nozzle pressure fluctuation for this condition also. Note the much higher nozzle pressure level for emulsion, also characteristic of any condition above ground idle, which may be due in part to the partial clogging of the nozzle screen with rust, paint, etc., as mentioned earlier. Bench test indicated that a higher pressure level should be anticipated, however.

Figures 36 and 37 are recordings of rapid decelerations. Once more the emulsified fuel appeared to slow down the engine response, but the effect on elapsed time was easily the greatest. All these increased times may be explained by the fact that the compressibility of the fuel causes a delay in

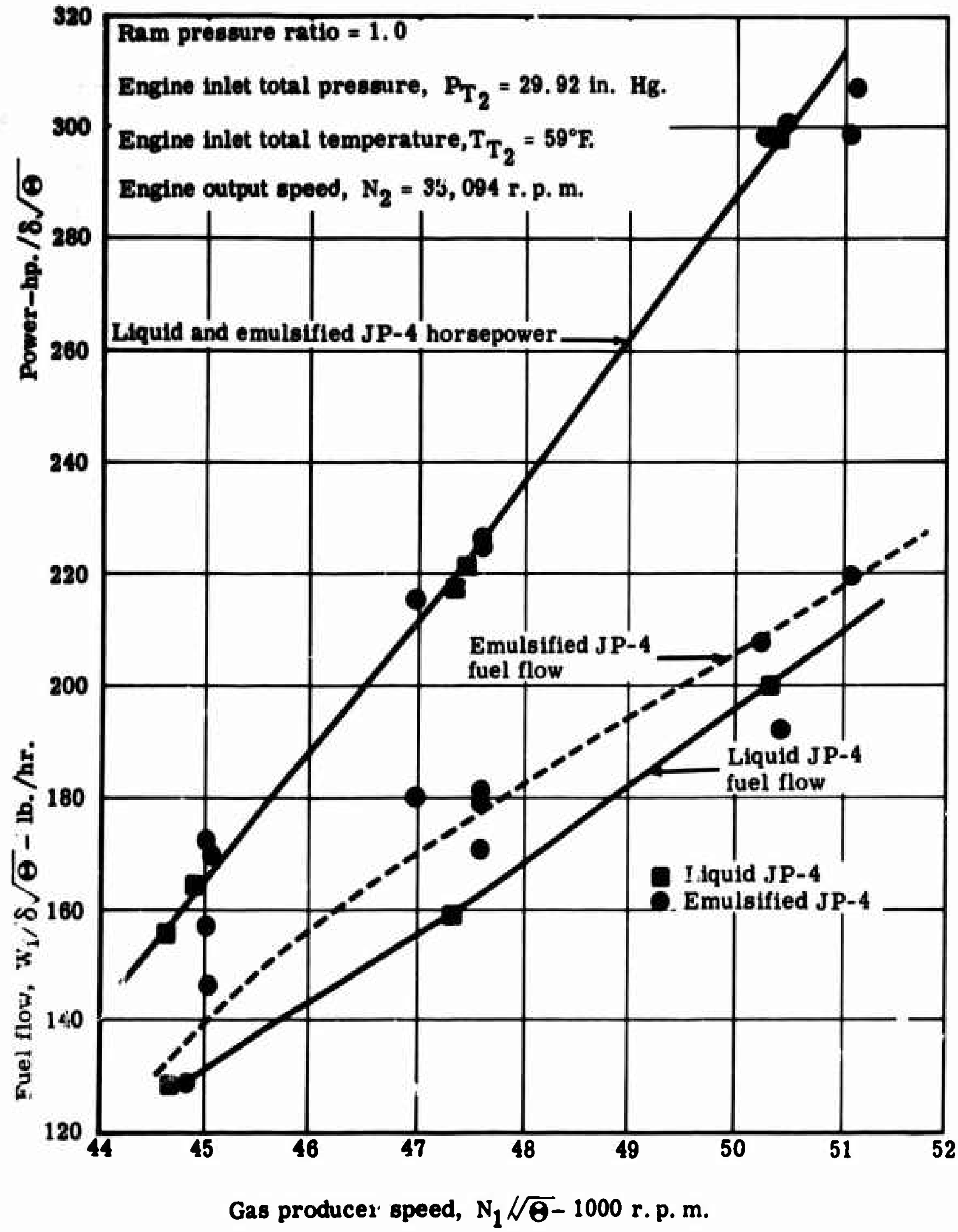

Figure 30. Both horsepower and fuel flow versus gas producer r.p.m. while burning liquid and emulsified JP-4.

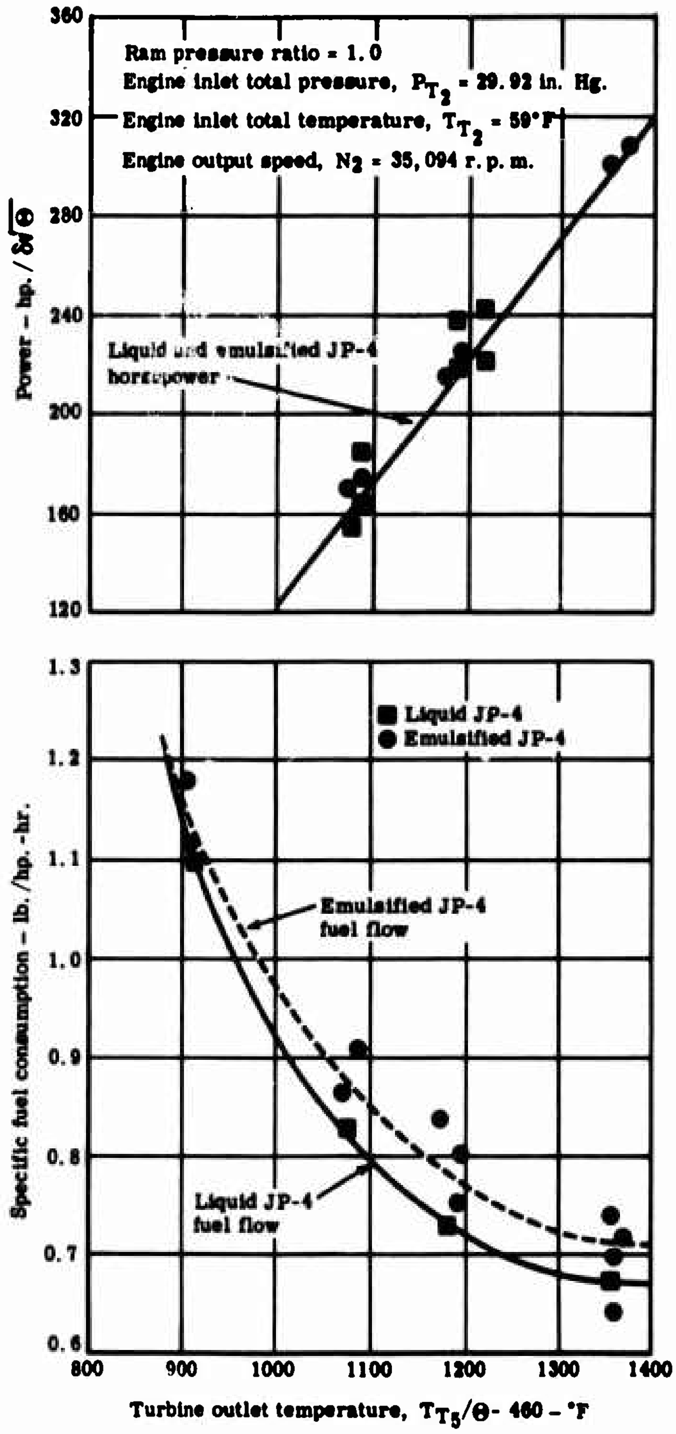

Figure 31. Both horsepower and specific fuel consumption versus turbine outlet temperature while burning liquid and emulsified JP-4.

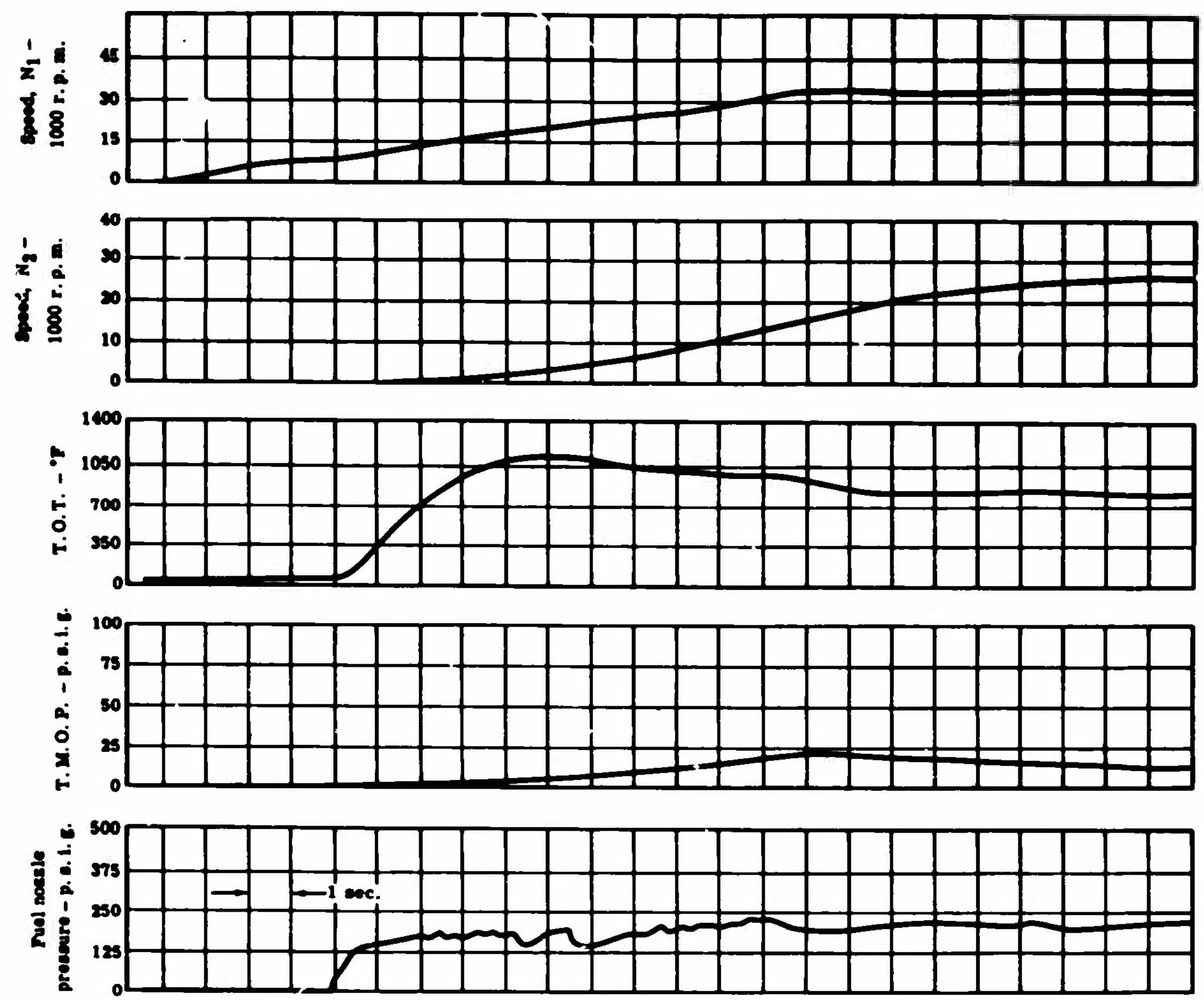

Figure 32. Reproduction of recorder chart showing five engine parameters versus time during a fire-up to ground idle while burning liquid JP-4.

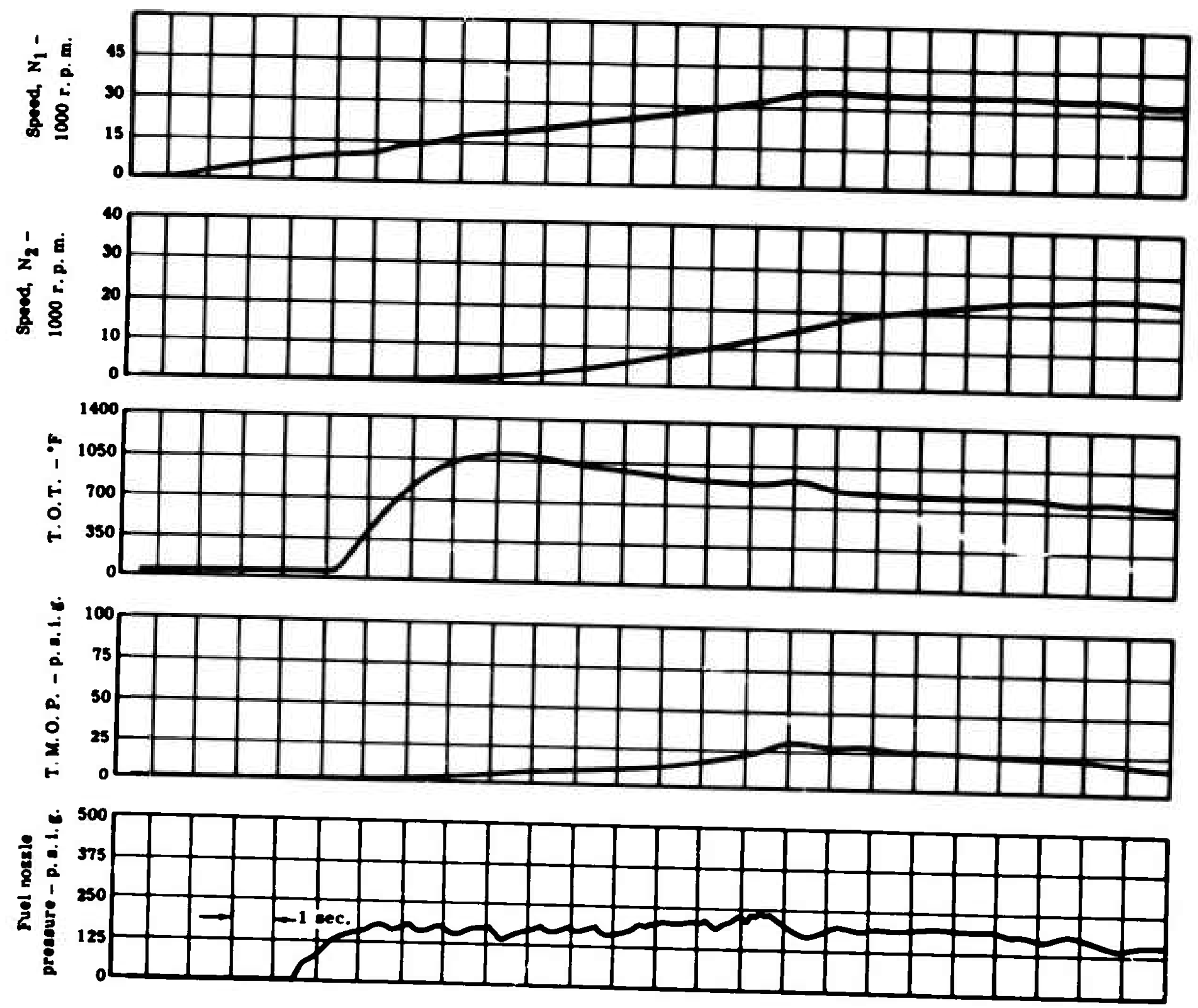

Figure 33. Reproduction of recorder chart showing five engine parameters versus time during a fire-up to ground idle while burning emulsified JP-4.

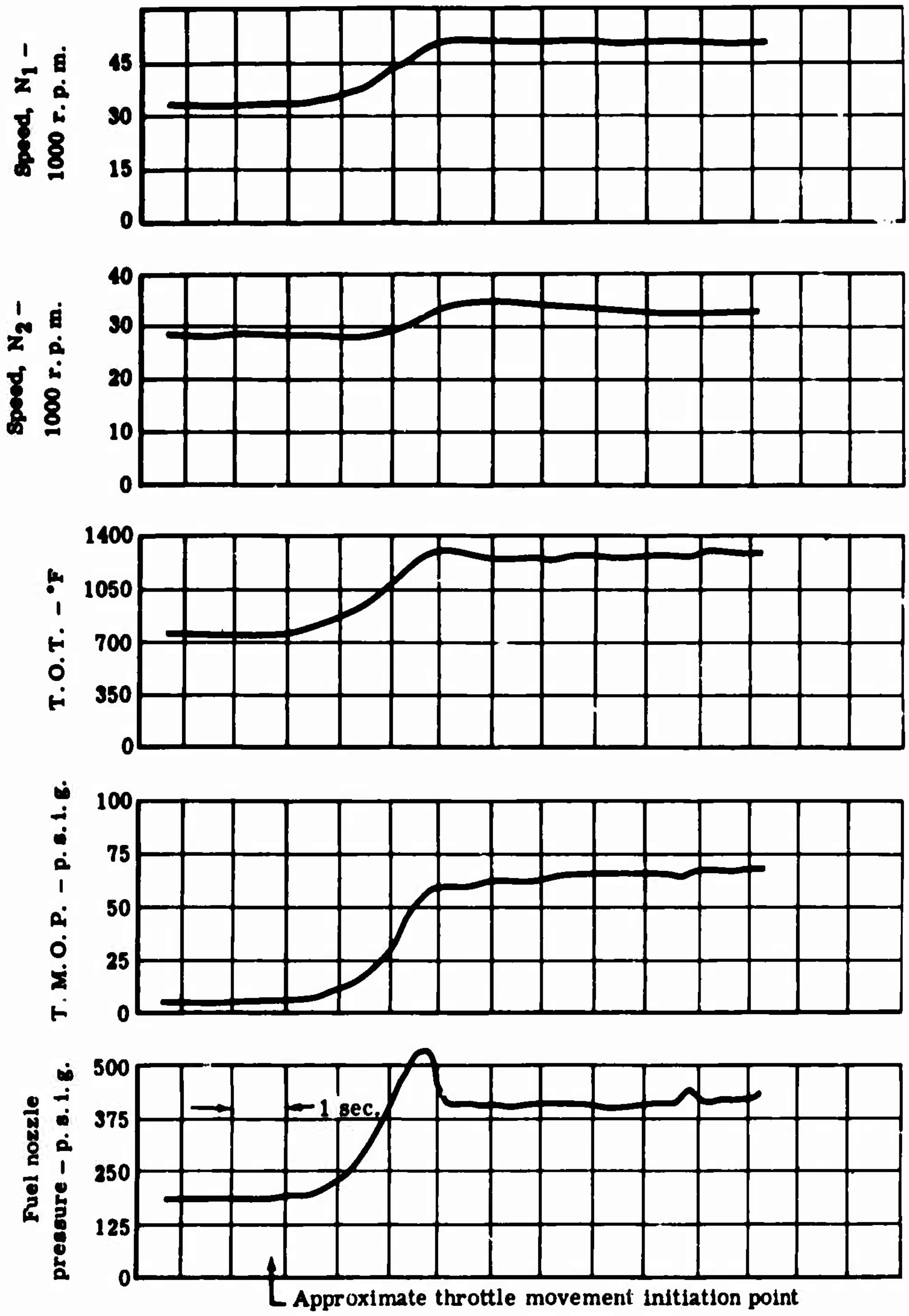

Figure 34. Reproduction of recorder chart showing five engine parameters versus time during a rapid acceleration from ground idle to takeoff while burning liquid JP-4.

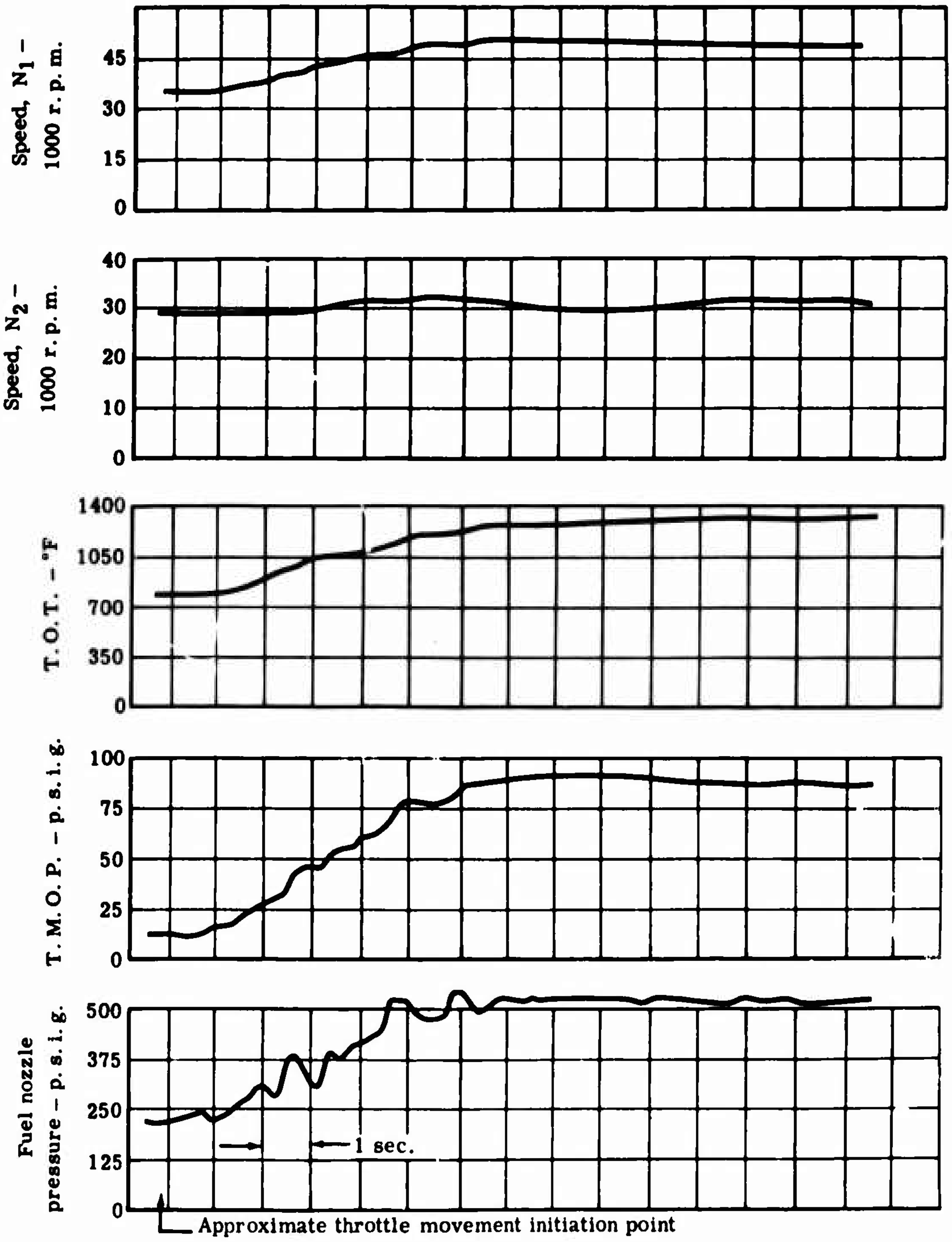

Figure 35. Reproduction of recorder chart showing five engine parameters versus time during a rapid acceleration from ground idle to takeoff while burning emulsified JP-4.

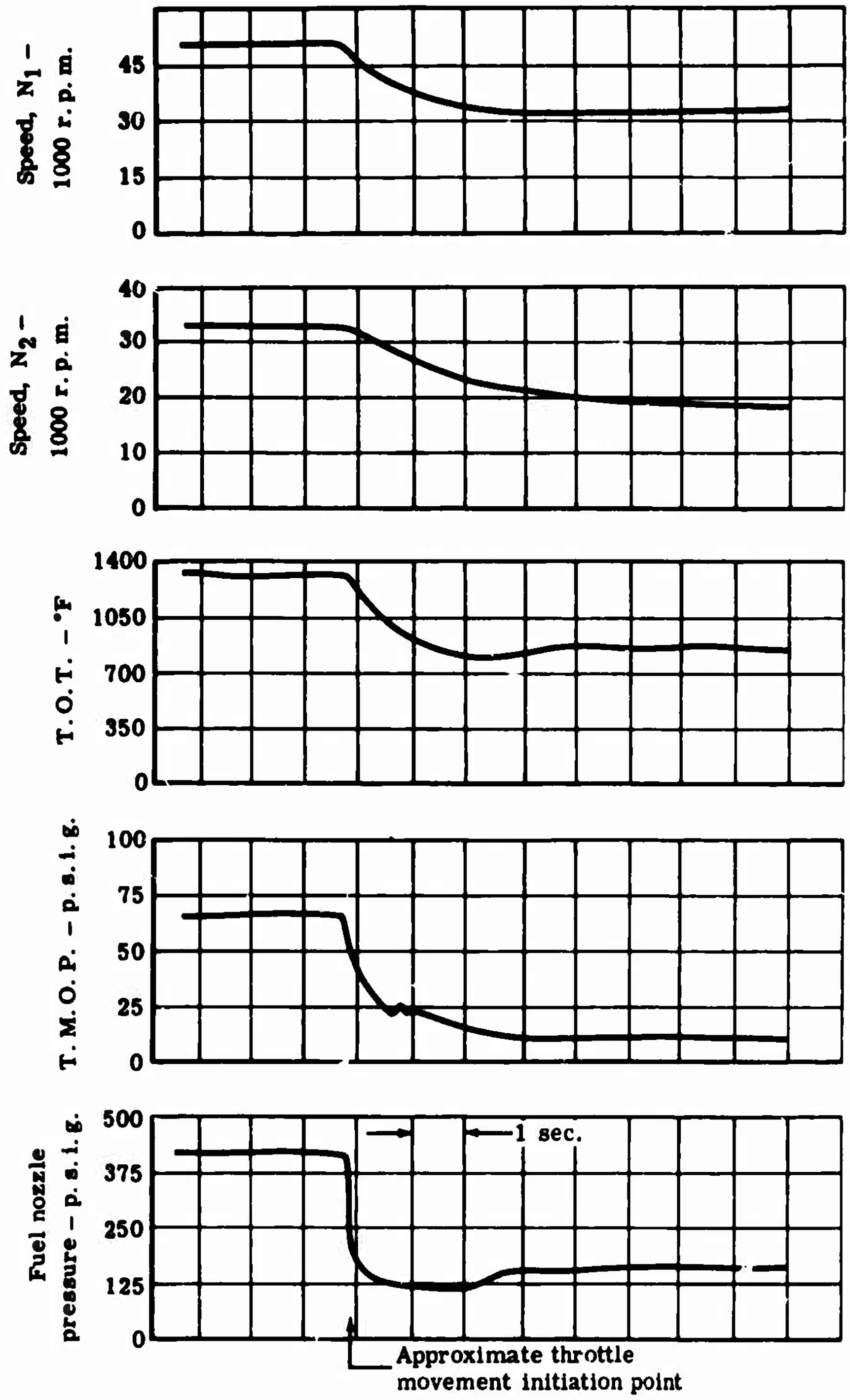

Figure 36. Reproduction of recorder chart showing five engine parameters versus time during a rapid deceleration from takeoff to ground idle while burning liquid JP-4.

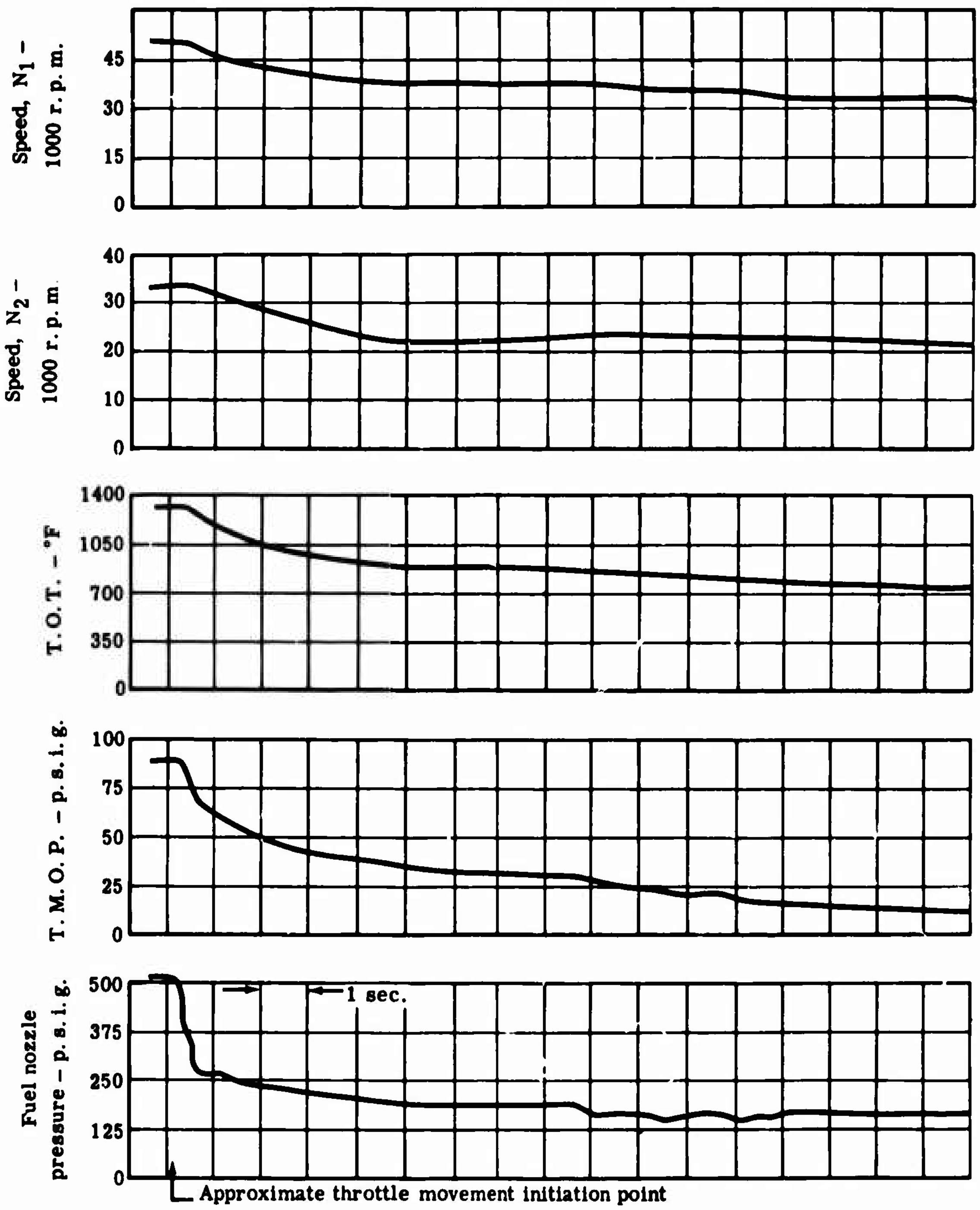

Figure 37. Reproduction of recorder chart showing five engine parameters versus time during a rapid deceleration from takeoff to ground idle while burning emulsified JP-4.

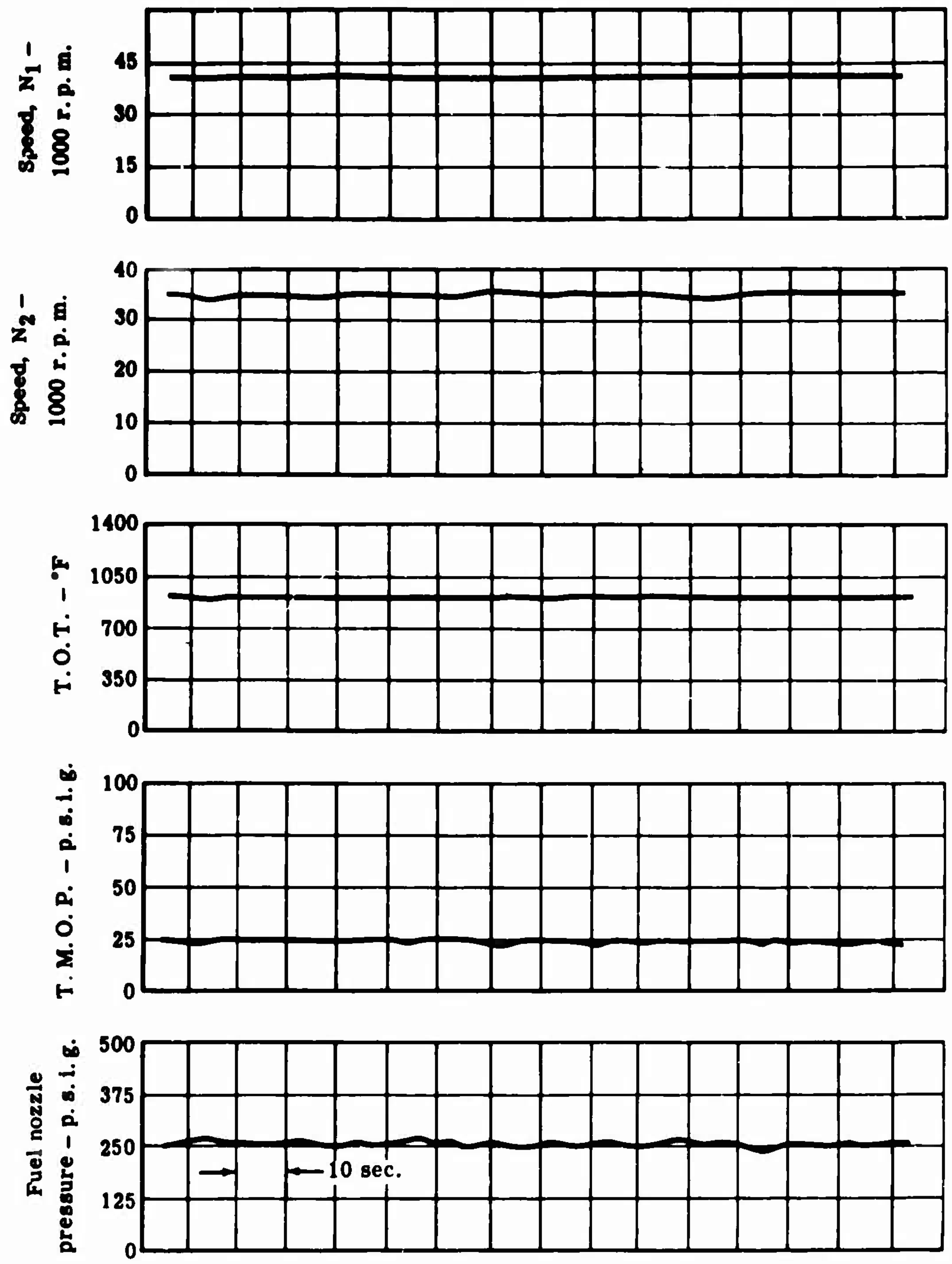

Figure 38. Reproduction of recorder chart showing five engine parameters while running at part throttle, 40, 346 gas producer r.p.m., while burning emulsified JP-4.

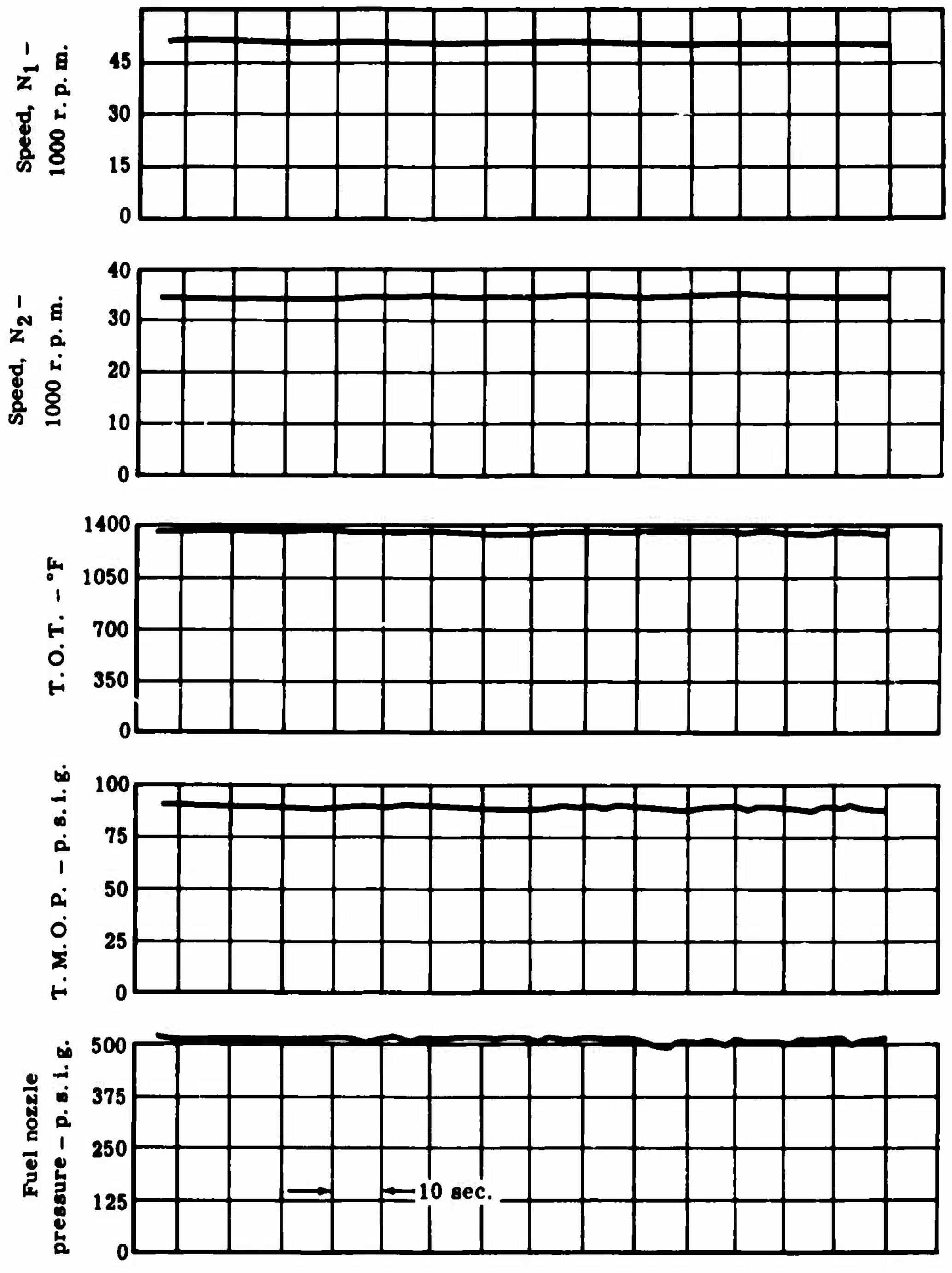

Figure 39. Reproduction of recorder chart showing five engine parameters running at takeoff, 50,993 gas producer r. p. m., while burning emulsified JP-4.

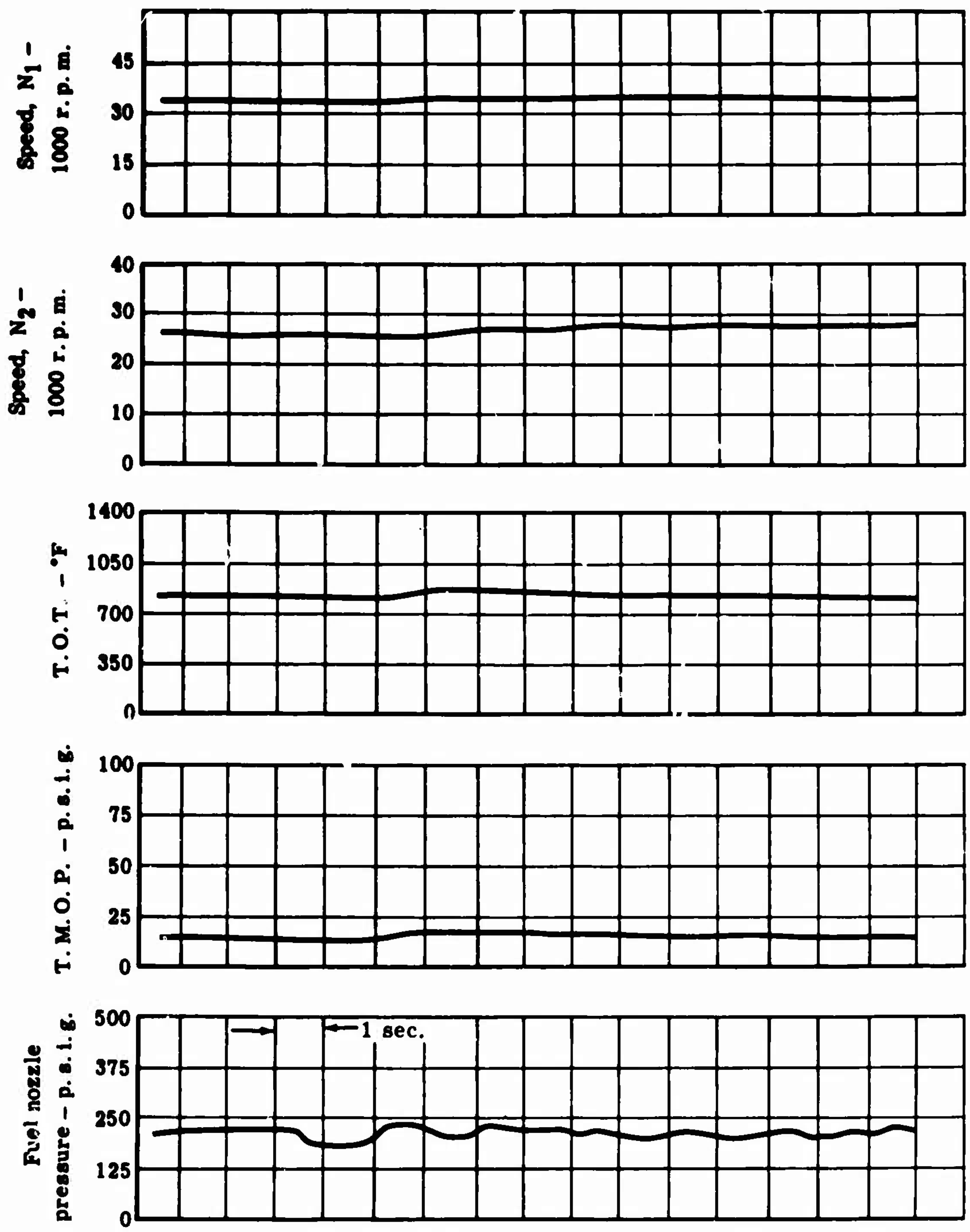

Figure 40. Reproduction of recorder chart showing transition from liquid to emulsified JP-4 while running at ground idle.

nozzle manifold pressure level change and a resulting delay in nozzle inlet pressure change. In general, the emulsion did not cause an excessively sluggish "feel", but the lack of response was evident to the operator.

Figures 38 and 39 show steady-state performance at two widely spaced levels. In both cases the fluctuations in nozzle pressure are evident. Similar traces for JP-4 burning showed nozzle pressure to remain steady. Note that the other parameters are stable and that the pressure instability does not result in engine instability.

A better comparison between liquid and emulsion running can be observed in Figure 40. The transition between liquid and emulsion occurred at ground idle. As can be seen, the top four parameters change level slightly but remain constant. Nozzle pressure alone becomes erratic.

Engine teardown revealed that the burner can, blades, vanes, and associated parts washed by engine exhaust gases were either rusted or coated with and abraded by a substance similar to jeweler's rouge but believed to be very fine rust particles. There was no evidence of excessively burned vanes or blades. The abridged performance calibration performed on liquid JP-4 during the last hour of emulsified fuel running time indicates that no serious performance depreciation occurred as a result of the operation on the emulsified fuel.

In conclusion, it can be said that fire-up, steady-state, and transient performance can be obtained satisfactorily while burning emulsified fuel if rust can be eliminated from the fuel system. Unfortunately the emulsified fuel washed rust particles originating from the Westco supply rig and the test stand fuel system into the engine. There is, however, sufficient evidence to indicate that when enough fuel is delivered in a system not clogged with rust particles, the engine will run in a manner comparable to that when liquid fuel is burned.

PART 3. LYCOMING, T-53

by
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Avco Lycoming Division
Stratford, Connecticut
Contract DA 44-177-AMC-453(T)

INTRODUCTION

BACKGROUND

A significant percentage of aircraft accident fatalities result from fire and not from the crash itself. From 1956 to 1965 the loss from fire damage in aircraft accidents, principally from ignition of flammable fluids, was in excess of $800 million.

Research efforts aimed at reducing the fire hazard in aircraft accidents have shown emulsified fuel to offer a promising solution. Emulsification produces a dispersion of the fuel in the water, the resultant product having a semisolid consistency. Emulsified fuel has a significantly lower evaporation rate than does JP-4 fuel. The variance of vapor explosibility as determined by the Petrolite Corporation is such that, in 15 minutes, a container of EF4-101 (97.5-percent emulsion) accumulated only 20 percent of explosive vapors while the JP-4 fuel generated 90 percent. The propagation of flame along a 10-foot trough containing JP-4 fuel, as determined by 8-millimeter motion pictures, required approximately 2 seconds, while with EF4-101 it required nearly 2 minutes. These characteristics render the emulsified fuel more easily contained and, in addition, reduce the threat from small arms fire.

RELATED EXPERIENCE

Prior to the work under the subject contract, Avco Lycoming Division had tested emulsified fuel in T53 engine operation. This engine was a T53-L-11 gas turbine incorporating a T53-L-13 atomizing combustor. These tests, conducted under sea level conditions, showed successful engine operation and demonstrated compatibility between emulsified fuel and the atomizing combustor. The atomizing combustor fuel system, with its higher fuel manifold temperatures combined with the shearing of the emulsion as it passes through the atomizing nozzles, breaks down the emulsion at or before its entry into the combustor.

The T53-L-13 engine now in production is the only T53 engine model with an atomizing combustor. T53-L-1/3/5/7/9 and 11 engine models use vaporizing combustors.

TEST ORIENTATION

Under contract to the U. S. Army Aviation Materiel Laboratories, Avco Lycoming Division in Stratford, Connecticut, conducted a two-phase program of emulsified fuel testing. Phase I covers the bench testing of the T53-L-11 engine fuel system components to ascertain whether a 97-percent fuel emulsion could be satisfactorily delivered through the fuel system. Phase II covers the operation, with emulsified fuel, of a T53 engine incorporating a vaporizing combustor.

In Phase I, a TA-2G fuel control from a T53-L-11 engine was mounted on a fuel bench test stand. Following the calibrations with MIL-F-7024A Type II calibrating fluid and JD-1 (emulsified JP-4) fuel, the T53-L-11 engine fuel components were connected to the fuel control (Figure 41). These fuel system components, in addition to the fuel control, were a T53-L-7 fuel-to-oil heat exchanger, a main fuel filter assembly, a bypass filter, a main fuel manifold assembly, a starting fuel solenoid valve, and starting nozzles.

In Phase II, a T53-L-7 engine was mounted in the outdoor variable attitude test stand. Because a T53-L-11 engine was not available for this program, use was made of a T53-L-7, which is similar. (The T53-L-11 engine is a turboshaft version of the T53-L-7 engine.) T53-L-7 Engine F-24F had been run in the Extended Service Life Program since March 1964, and to date has been test operated in excess of 3300 hours. In preparation for testing, the gas producer turbine nozzle, gas producer turbine rotor, and combustor assembly were replaced with like hardware previously used in T53-L-7/11 engine development.

FUEL EMULSIFICATION

A fuel emulsification and pumping system (Figures 42 through 44) produced by the Western Company of Dallas, Texas, was employed in the conduct of this program. The emulsion (JD-1) was prepared in accordance with a detergent formula developed by the Western Company. In making 50 gallons of the 97-percent emulsion, a mixture consisting of 0.5 percent (0.25 gallon) Western MFE-11, 2.5 percent (1.25 gallons) of water, and 48.5 gallons of JP-4 fuel was used.

The fuel emulsification portion of the system console consists of a 55-gallon stainless steel tank to contain the fuel and a Roper gear pump to cycle the fuel and to provide the shear required for emulsification. The pump is driven by a Gerbing variable-speed drive connected to an explosion-proof, 2-horsepower, 220-volt, alternating-current, 3-phase motor. The motor is controlled by an explosion-proof switch. Fuel is

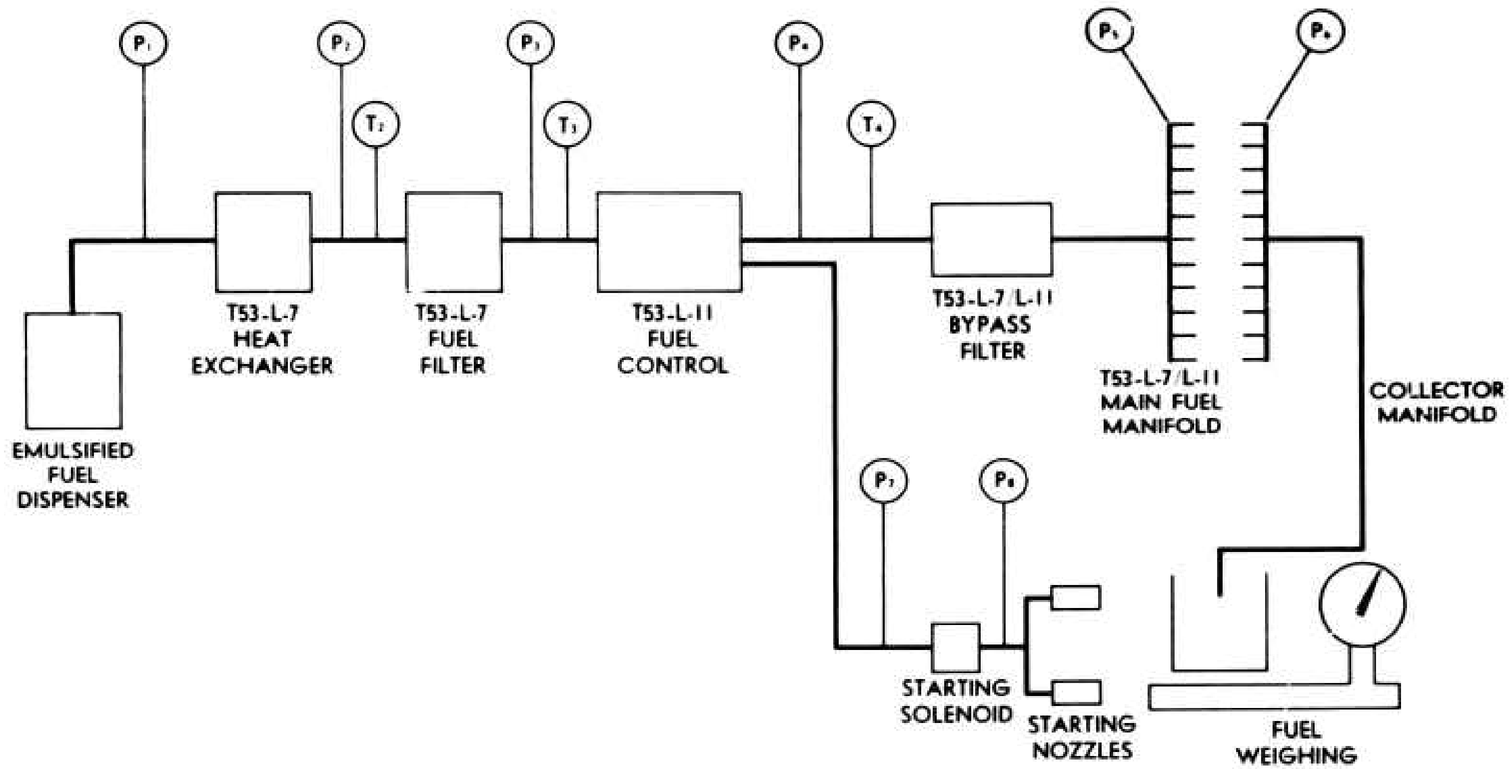


Figure 41. Bench Test Schematic.

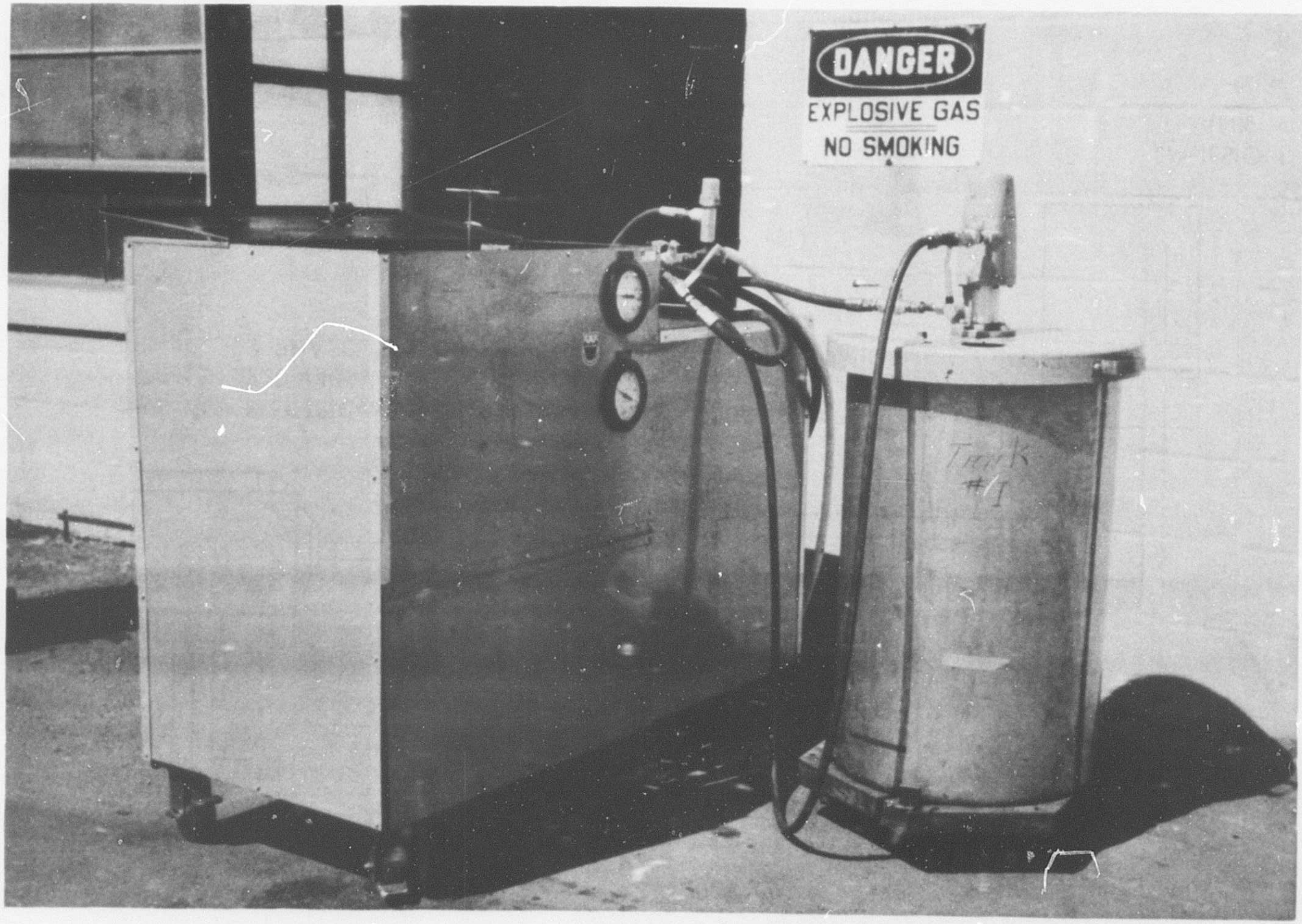


Figure 42. Western Company Emulsifying and Fuel Pumping Rig.

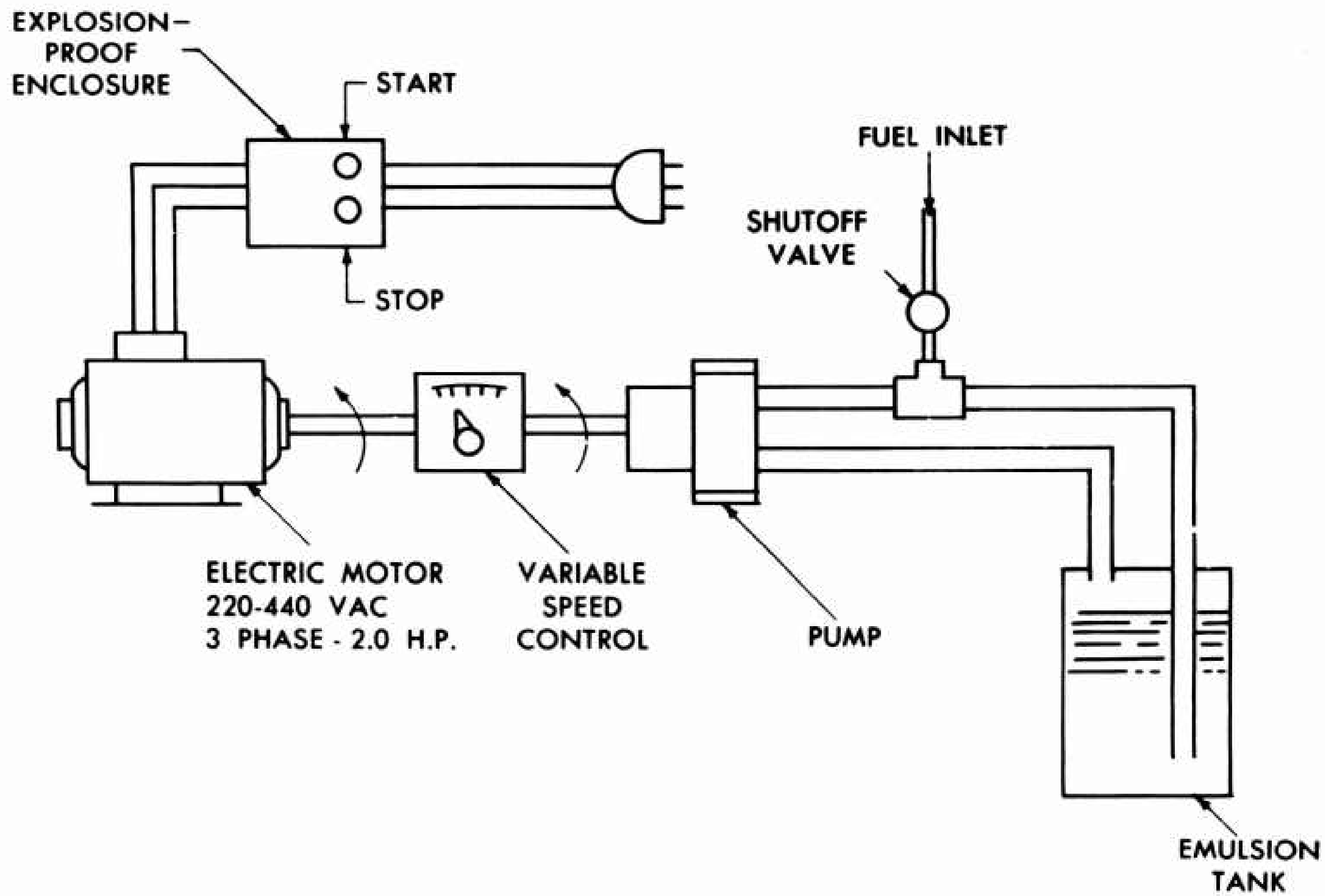


Figure 43. Western Company Emulsifying Schematic.

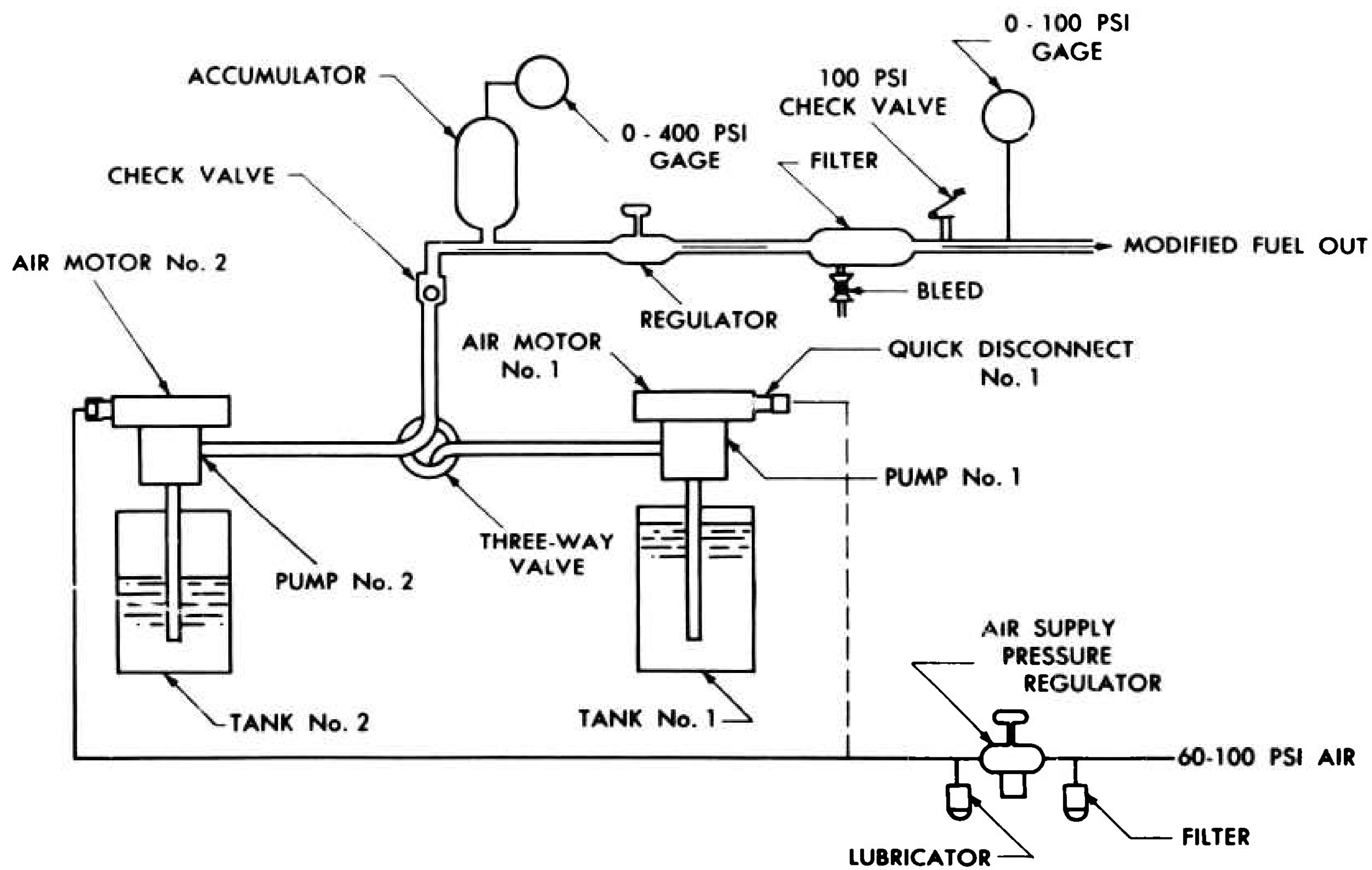


Figure 44. Modified Fuel Pumping Schematic of Western Company Emulsifying and Pumping Rig.

emitted by a needle valve into the inlet of the pump. The pumping portion of the console is used to feed the emulsified fuel into the fuel lines and to provide the boost pump pressure. It consists of two 55-gallon stainless steel tanks with air-powered piston pumps to remove the fuel from the tanks.

Each tank has a follower plate which rests on top of the fuel and which insures that air does not channel into the pump inlet. The outlets from the air-powered pump connect into a three-way valve which allows the fuel to be drawn from either barrel. From the three-way valve, the fuel passes through a check valve, an accumulator (pulsation dampener), a fluid pressure regulator, and a 100-micron filtration system. Pressure gages are provided to indicate the fluid output pressure (0 to 100 psi) and accumulator pressure (0 to 400 psi). The air supply to the piston pumps is furnished to the unit through a filter, pressure regulator, and lubricator combination. In order to deliver the emulsified fuel to the engine, the air-powered piston pumps from the console were used in conjunction with 55-gallon containers of JD-1 fuel.

Several problems were encountered in the preparation and delivery of emulsified fuel. Corrosion of console components resulted from the use of this fuel. Rust and scale were delivered to the system's 100-micron filter, which became clogged. Filter bypassing resulted, and harmful contaminant was delivered to the test hardware. This bypassing problem was corrected by installation of a three-filter system in the console. Corrosion of the console pump and follower plate was corrected by cadmium plating the components. Finally, a preservative oil was pumped through the system after its use on emulsion.

BENCH TEST

FUEL CONTROL CALIBRATION

A standard T53-L-11 fuel control manufactured by Chandler Evans was calibrated with MIL-F-7024A Type II calibrating fluid. Initial runs were performed with the emulsified fuel in a 5-hour period of running (Figure 45). During this period, the fuel dispenser rig was producing a partially broken-down emulsion. The rig was also generating rust and scale from corrosion of internal piping. At this time, the filter in the dispensing rig was not operating correctly, and much of the contaminant entered the fuel control. The fuel barrier filter upstream of the fuel control showed a pressure drop of 9 psi at 200 pounds per hour flow, indicating that it was on bypass and giving the control no protection against contamination (Figures 46 and 47). In these tests, the control did not generate the correct schedules and ultimately delivered no flow at all. On disassembly, it was found that rust particles had accumulated in the pressure regulating valve and caused excessive wear in the valve sleeve. The valve appeared to have stuck in the open position, causing all the pump output to be recirculated. This recirculation caused excessive heat, which, in combination with the contaminant, caused pump wear. No other internal damage or deterioration was found. The control was washed out, cleaned, and dried, then recalibrated with calibrating fluid after a new pressure regulating valve was installed. Recalibration indicated that the control was in satisfactory condition for continued testing, and the figures from this run were used as the base-line points in the fuel control curves (Figure 48).

Prior to the resumption of the fuel control calibration with emulsified fuel, an improved filtration system had been installed in the rig. The emulsion quality was quite good, not broken down as in the initial run. The calibration was obtained of the 59°F acceleration, takeoff droop, and deceleration schedules, with fuel temperatures of 70°F and 180°F. The schedules were essentially the same as those obtained when calibrating fluid was used, as far as could be judged within the limited accuracy of the flow measurement.

TEST DESCRIPTION

Following the fuel control calibration with emulsified fuel, the bench test of the engine fuel system was set up as shown in Figure 41. The JD-1 fuel was pumped from the fuel dispenser through a T53-L-7 heat exchanger and fuel filter, to the fuel control, to the bypass filter, to the main fuel manifold, and then collected in a collector manifold. In addition, emulsified fuel was taken from the metered starting fuel port on the fuel

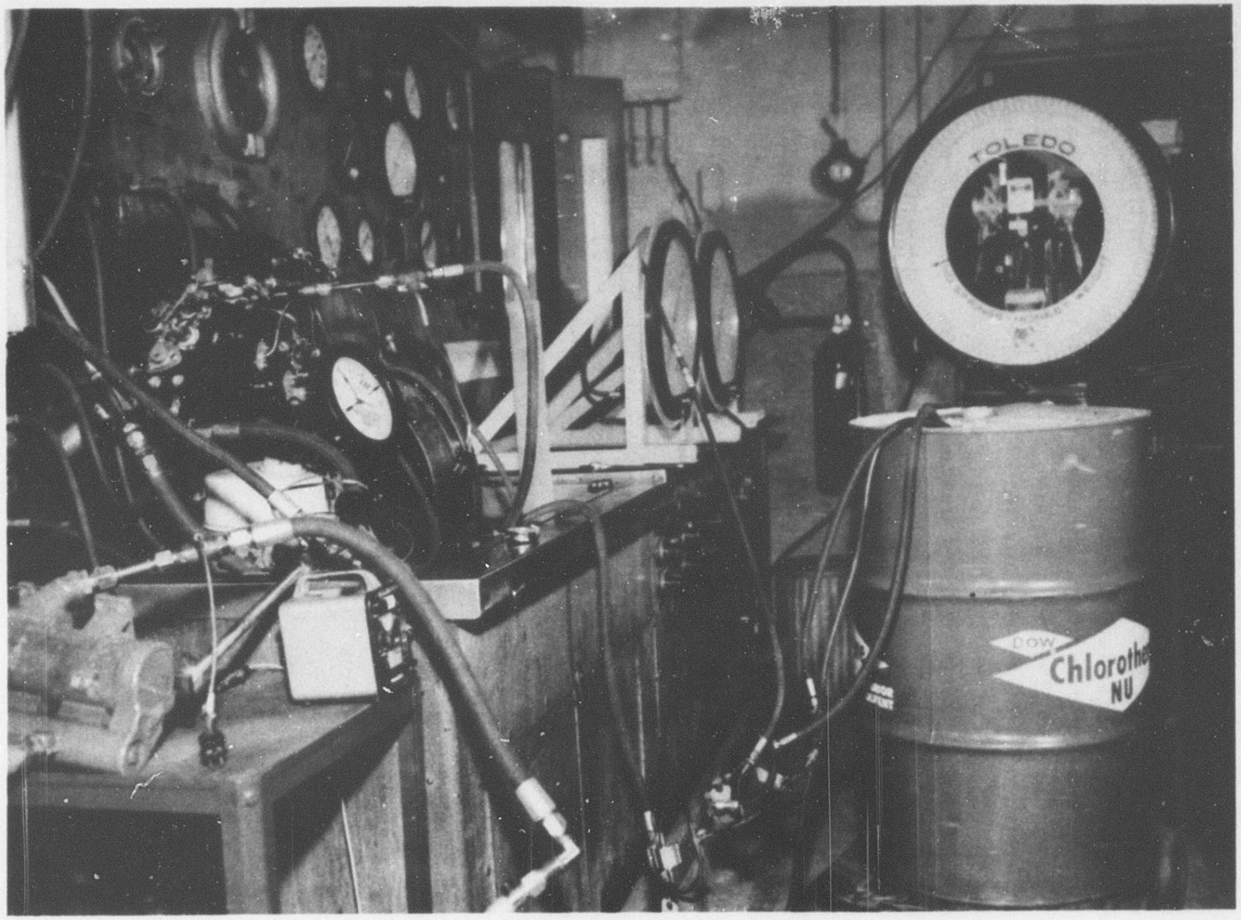


Figure 45. Fuel Control on Flow Bench Being Calibrated With JD-1 Fuel.

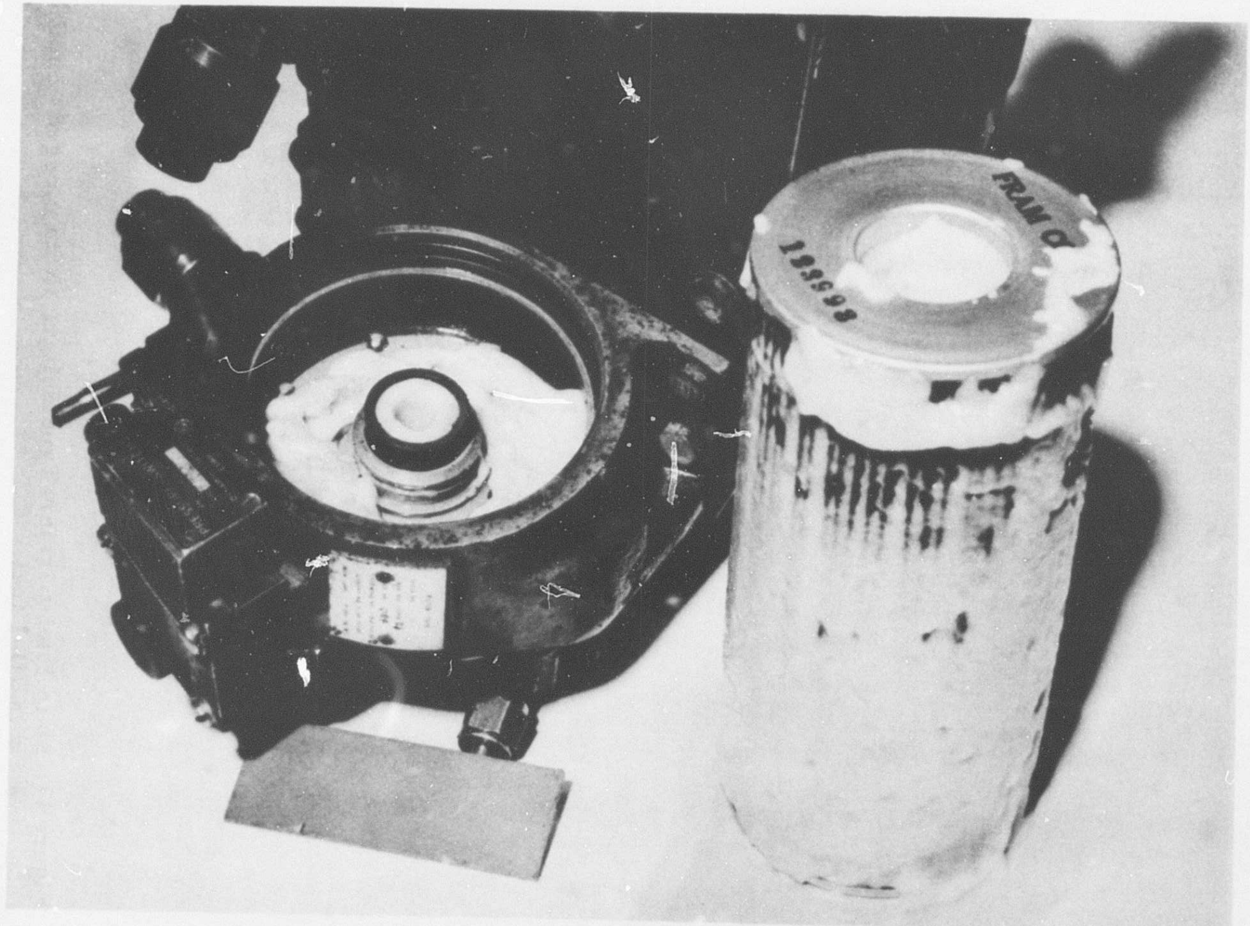


Figure 46. Main Fuel Filter Body and 10-Micron Barrier-Type Filter.
(Note clogged condition with JD-1 fuel.)

Figure 47. Main Fuel Barrier-Type Filter. (Note clogged condition with JD-1 fuel.)

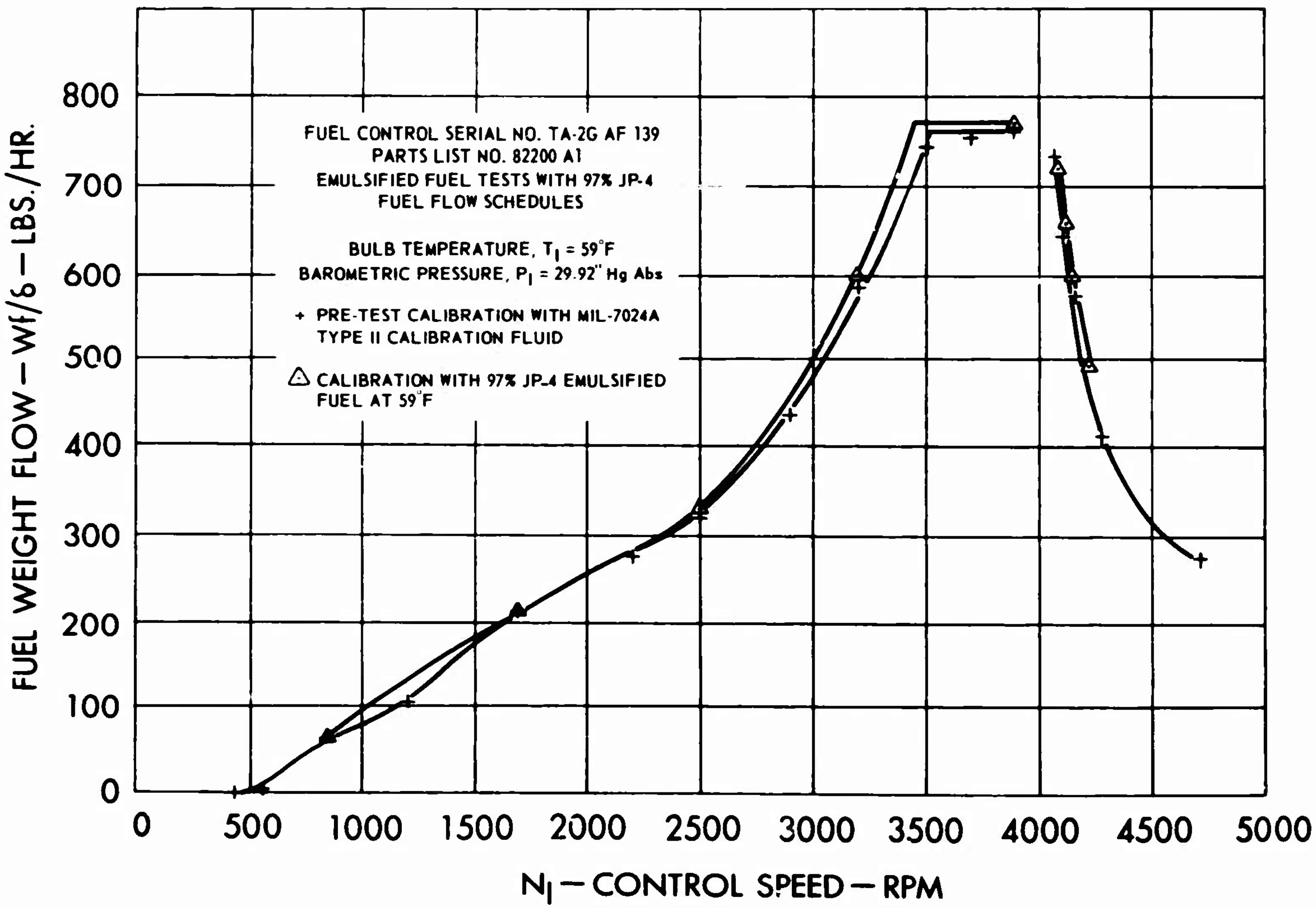


Figure 48. Fuel Control Calibration Curve.

control through the starting solenoid valve to the starting nozzles. Emulsified fuel from the fuel control was flowed to the main fuel system and starting system. Fluid pressures were read on Bourdon tube pressure gages, and fuel flows were measured by weight for the main fuel system and by volume for the starting fuel system. Fuel temperature was approximately 72°F.

No change was noted in the flow schedule of the metering injectors of the main fuel manifold when flowing emulsified fuel at 72°F compared with that of the original calibration when using calibration fluid.

Inspection of the fuel flowing from the fuel manifold showed no visual change from that being emitted from the fuel control, which shows that emulsified fuel was not being broken down by the fuel metering injectors.

No noticeable increase in pressure drop across the bypass fuel filter was noted when flowing emulsified fuel compared to that of the original calibration. This shows that the emulsified fuel did not clog the 0.005-inch (125-micron) diameter openings in the filter element, which would have caused the assembly to bypass fuel and allow harmful contamination to pass onto the injectors.

No increase in pressure drop across the starting fuel solenoid valve was noted when using emulsified fuel. The opening and closing operation of the valve was normal.

POSTTEST CALIBRATION

Throughout the test, the pressure drop across the main metering valve fluctuated from 15 to 27 psi in an irregular oscillation. This fluctuation indicated that the pressure regulating valve was unstable due either to entrapped air behind the diaphragm or to the varying viscosity of the fuel. During the final 2 hours of bench testing with emulsified fuel, attempts were made to obtain ground idle n_I droop schedules, but the n_I droop servo amplifier valve appeared to stick, there being no change in fuel flow with speed change.

A posttest calibration with calibrating fluid revealed loss of a start schedule with no fuel output below 800 rpm control speed (19-percent compressor speed). This was due to the loss of fuel pump delivery and was confirmed by an independent calibration of the pump. All other schedules (59°F acceleration, takeoff, and ground idle droops and deceleration) appeared satisfactory.

POSTTEST INSPECTION

Posttest inspection revealed pump wear. The replacement pressure regulator valve showed no wear, and the leather cup seals removed from the P_I servo amplifier valve were in good condition. Rust deposited on the pressure regulator valve sleeve is shown in Figure 49. It was noted that all the servo amplifier valves were extremely stiff due to the dry condition of the "O" seals on the valve stems. The fuel control housing and computer assembly had extensive rust deposits, which were easily wiped clean (Figures 50 through 52). It is thought that this rust was deposited in the control from the fuel, which carried it in suspension from the fuel dispenser rig. The control inlet fuel screen contained a sand-like powder analyzed as lint, rust, and dust. A white powdery substance on the computer housing was found to be from corrosion of the anodized surface. The sodium dichromate sealer had also been attacked, allowing corrosion of the aluminum casting (Figures 50 through 53).

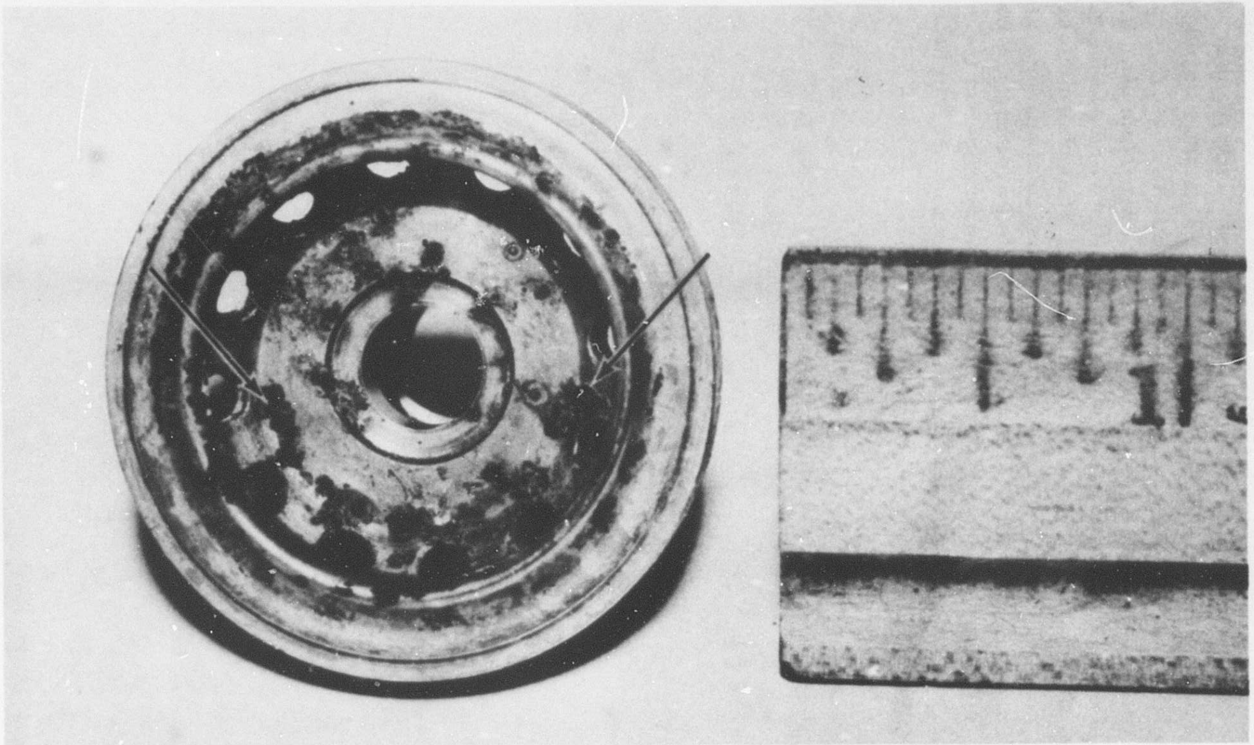


Figure 49. Pressure Regulator Valve Sleeve. (Note rust deposits.)

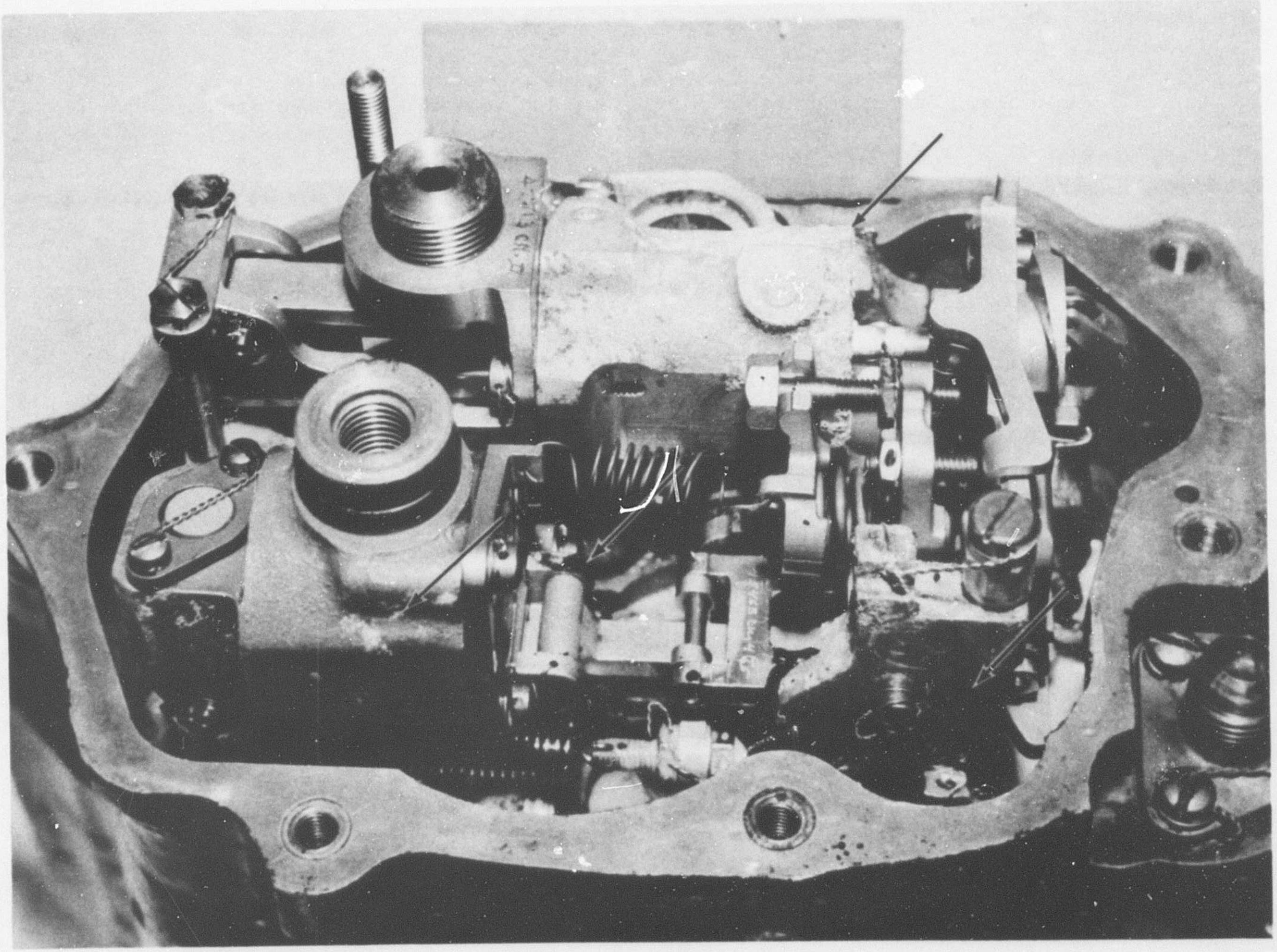


Figure 50. Fuel Control Computer Assembly; Overall View. (Note rust deposits and corrosion of the anodized surfaces.)

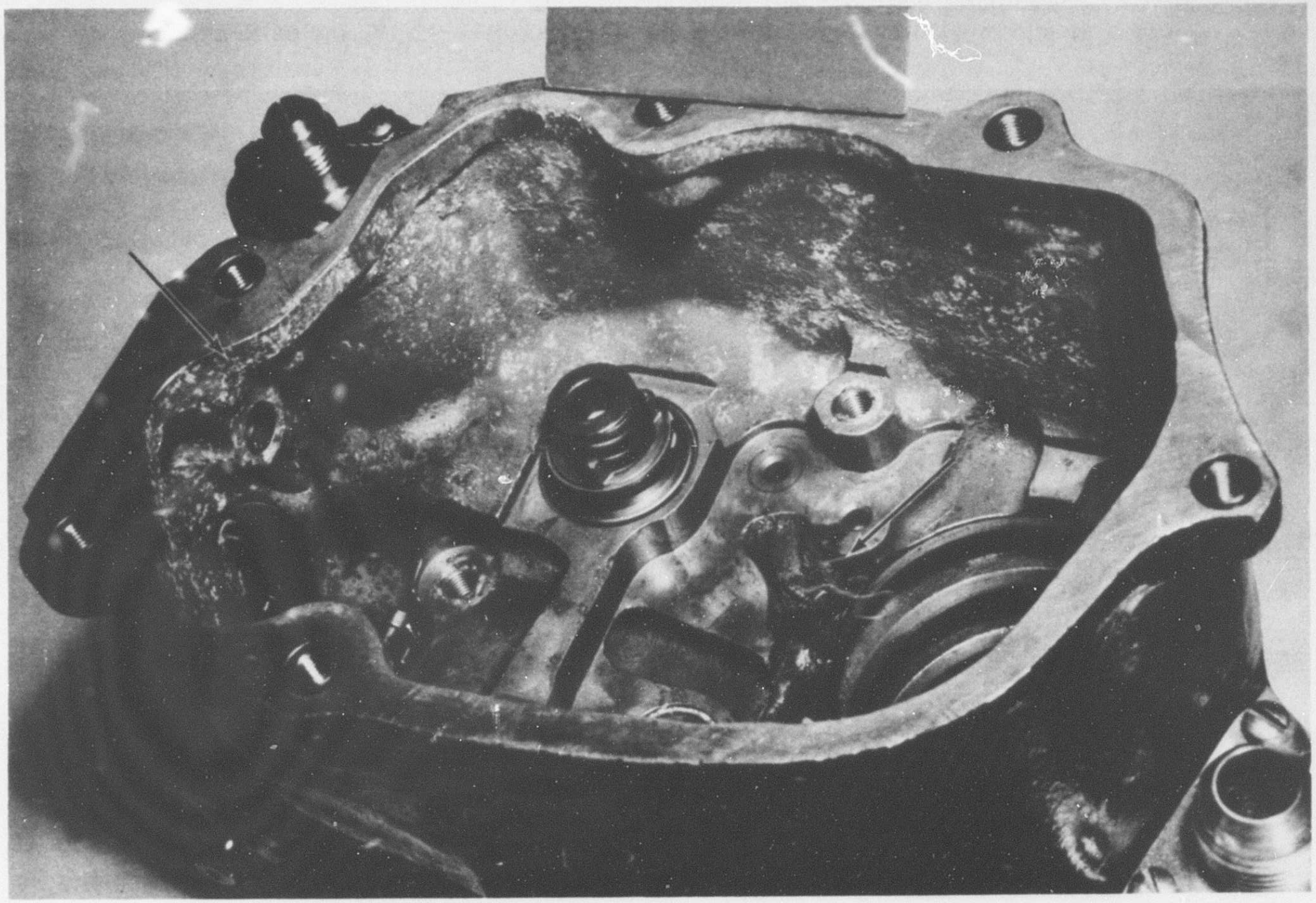


Figure 51. Fuel Control Housing. (Note rust deposits and corrosion of the anodized surfaces.)

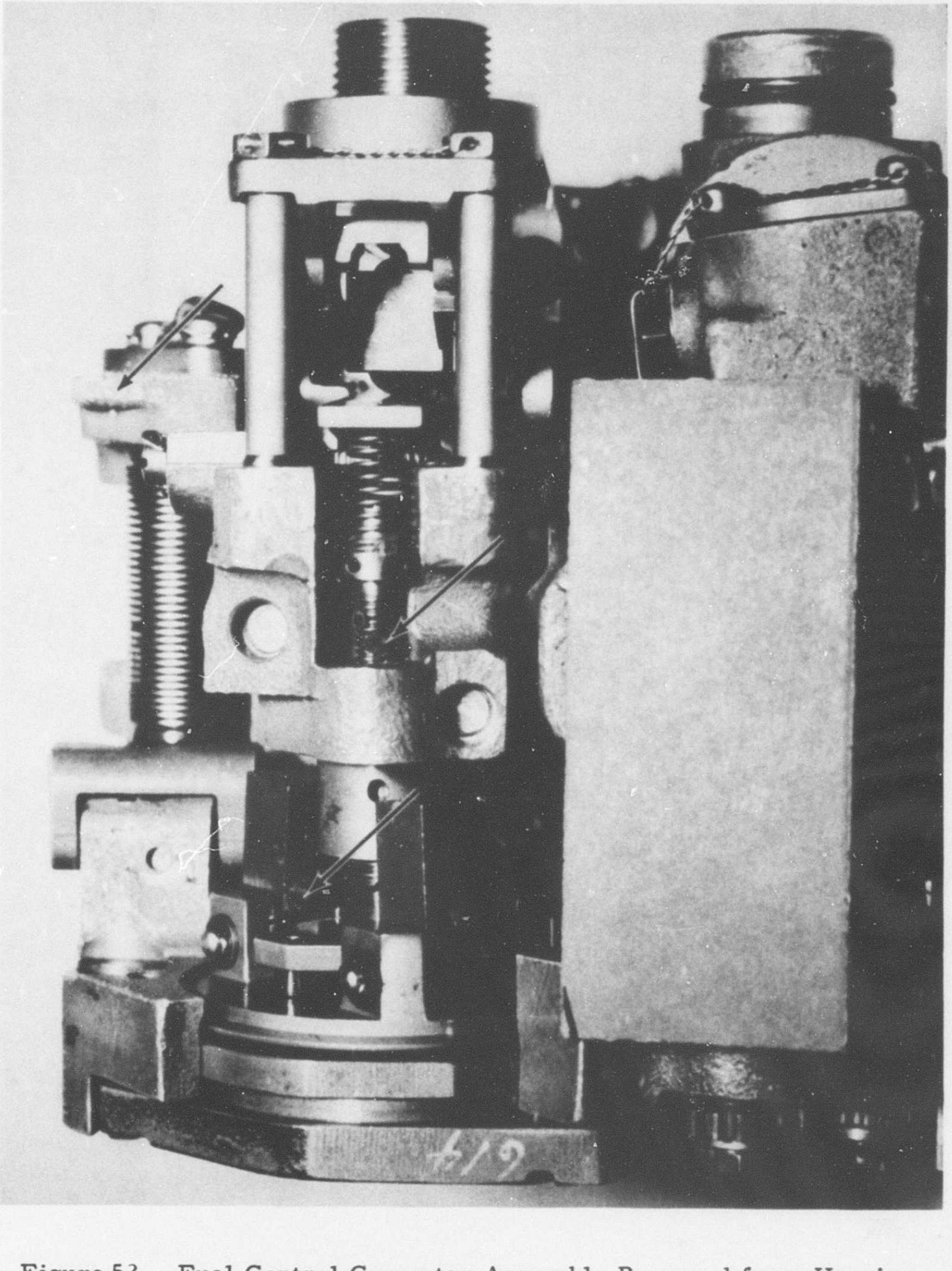


Figure 52. Fuel Control Computer Assembly Removed from Housing; End View. (Note rust deposits.)

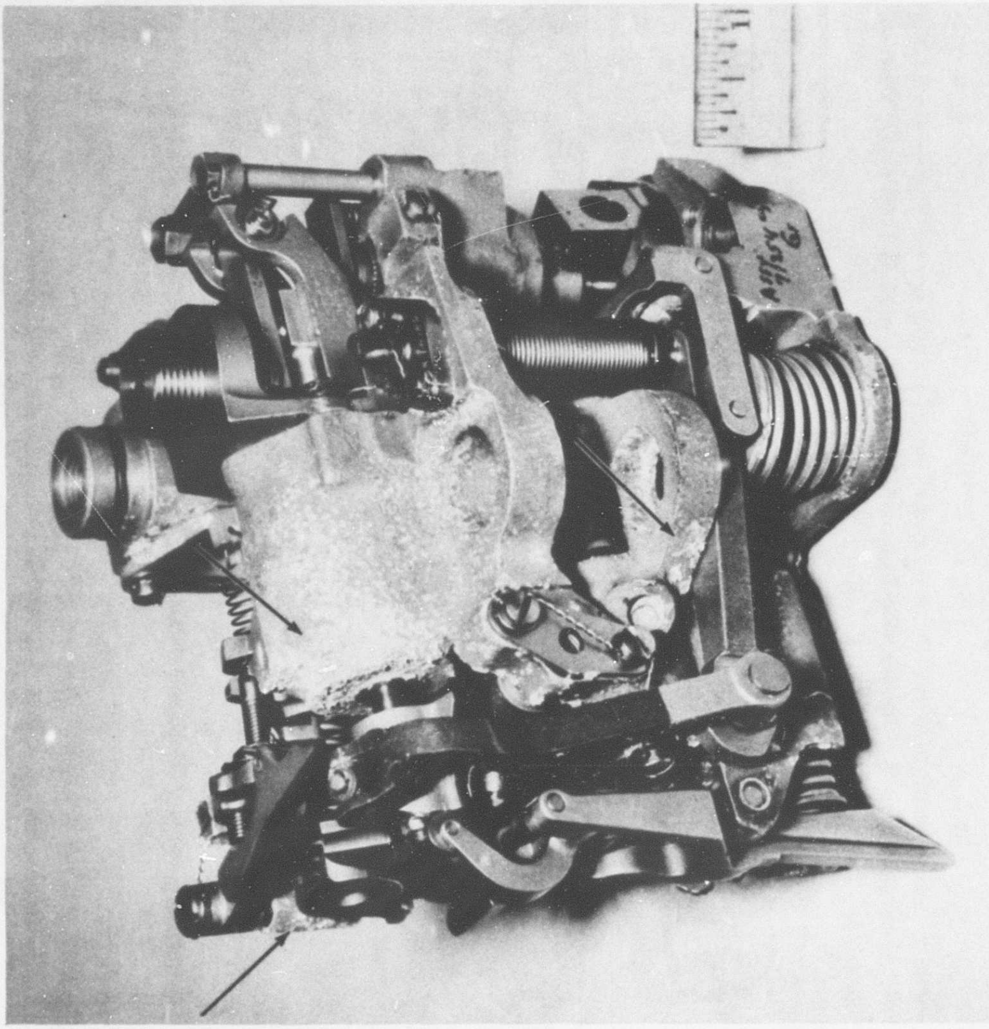


Figure 53. Fuel Control Computer Assembly Removed from Housing; Overall View. (Note corrosion of anodized surfaces.)

ENGINE TEST

The second phase of the study, which called for the operation of a turbine engine with emulsified fuel, was conducted on a turboprop version of the T53 engine series, the T53-L-7 engine. The engine, which incorporates a vaporizing combustor, was installed in a variable-attitude test rig and fitted with a Marvel test club propeller for power absorption. A brief description of the combustor is given below.

ENGINE COMBUSTOR DESCRIPTION

The T53-L-7/11 engine combustion chamber is a reverse-flow, external annular design with a fuel vaporizing system. The "folded" design permits maximum utilization of space and allows for a short shaft between the turbines and compressor and power reduction gearing.

The combustor liner has perforations arranged to meter air into the combustor for combustion and cooling. Fuel is injected into 11 ceramic-coated stainless steel vaporizers, which are located at the rear of the combustor.

The vaporizing fuel system does not admit fuel into a cold engine in a combustible condition; therefore, the combustion starting system must provide sufficient heat to promote fuel vaporization. The starting hot-streak fuel nozzles and two spark igniters each located next to a starting fuel nozzle, provide the heat necessary for fuel vaporization and ignition.

Airflow during the starting phase is provided by rotating the compressor with an electric starter. As the gas producer starts to rotate, the primer fuel solenoid valve is energized, and fuel is allowed to enter the combustor chamber through the starting fuel nozzles, where it is ignited by the spark igniter plugs. As the engine speed further increases, fuel pressure also increases. A minimum pressure valve, the foot valve, in the fuel control opens and allows fuel to flow to the already preheated vaporizing tubes. The fuel is vaporized and stable combustion is initiated. As the engine then accelerates to the speed selected, the spark plugs are de-energized, and the starting fuel solenoid is closed.

The T53-L-13 engine atomizing combustor is also a reverse-flow, external annular design. It incorporates 22 main atomizing nozzles of dual-orifice design, four primer nozzles, and two dual-channel fuel manifolds. Each manifold supplies fuel to 11 main fuel nozzles. Fuel is supplied to a fuel divider which directs primary fuel through the aft channel in the manifolds. Secondary fuel flows through the forward channel of the

manifold and is programmed in the flow divider as a function of fuel flow in the primary system.

INSTRUMENTATION

Standard test cell instrumentation was used to measure the various engine operating parameters with the exception of fuel flow. Fuel flow was measured with a Flo-tron Corporation linear mass flowmeter. In addition, fuel flow was measured using a time-weight system (the emulsified fuel containers were placed on a 1000-pound scale). Transient data were obtained with pressure transducers, thermocouples, and mechanical pickups in conjunction with Sanborn amplifiers and oscillographs. The transient recording equipment was used to determine fuel flow (W_f), exhaust gas temperature (T_{t9}), throttle position (T_p), compressor discharge pressure (P_{s4}), gas producer speed (n_I), and power turbine speed (n_{II}). The standard cell instrumentation that was used to measure the engine variables during the test is as follows:

1. Standard Electric Time Corporation tachometer indicators and counters in conjunction with MS 28054 tachometer generators for measuring the compressor and power turbine speeds.
2. Mercury and water manometers and Bourdon tube gages for pressure measurement.
3. Iron-constantan and chromel-alumel thermocouples and high- and low-temperature self-balancing precision potentiometers for temperature measurement.
4. Consolidated Engineering Corporation miniature velocity pickups and vibration meter to measure engine vibration.

TEST DESCRIPTION

The engine was calibrated on JP-4 fuel. Transient operation with JP-4 fuel was demonstrated from ground idle to takeoff power and from flight idle to takeoff power. Figure 54 depicts the Sanborn trace of an acceleration from flight idle to takeoff power.

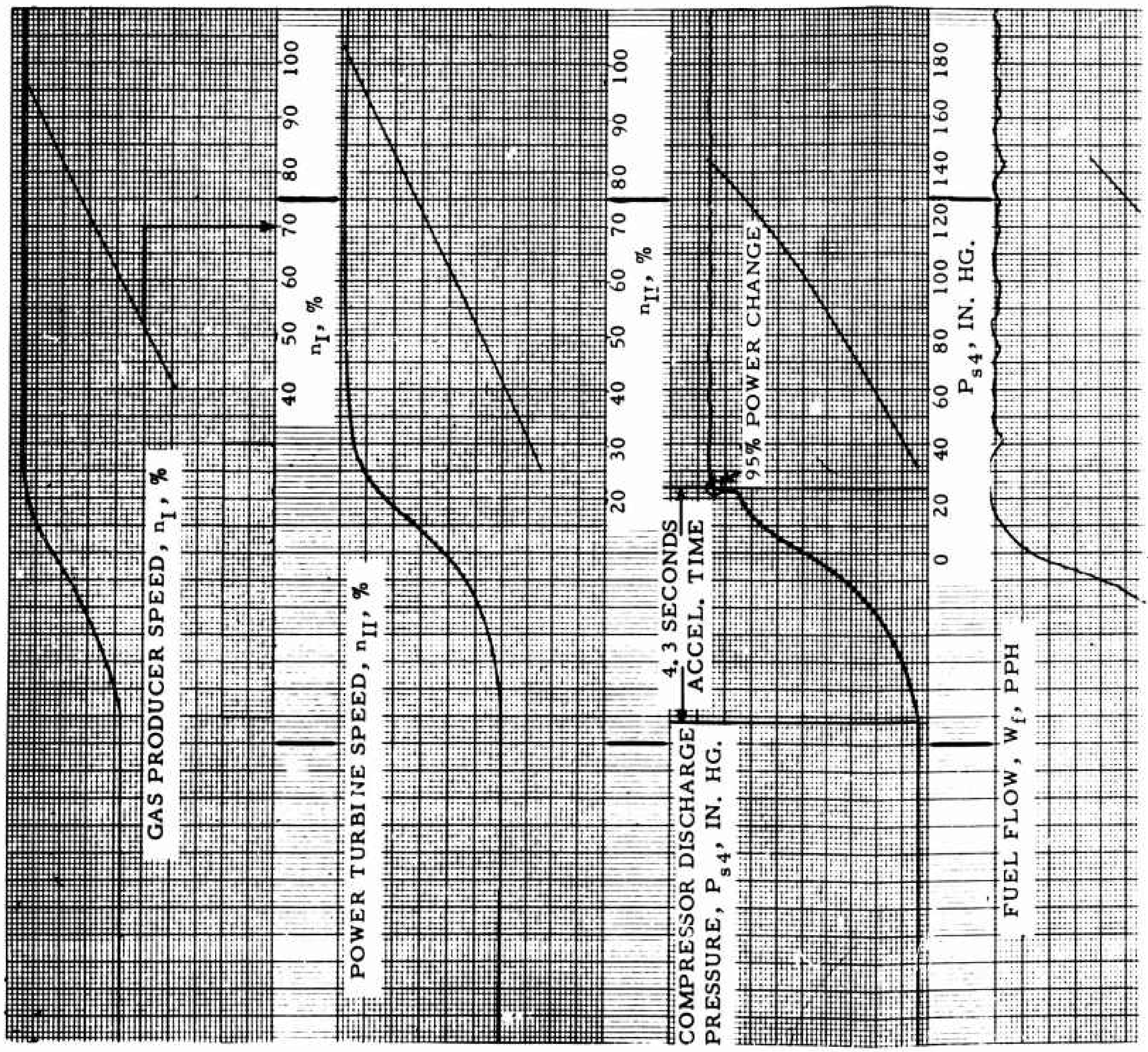
Initial attempts to start the engine were unsuccessful when the emulsified fuel was used at sea level conditions. During these attempts, the engine would light off on the hot-streak, atomizing starting nozzles; but due to inadequately vaporized fuel in the fuel vaporizers, stable combustion could not be obtained. Starts were accomplished on JP-4 fuel followed by a changeover to emulsified fuel. Changeovers to emulsified fuel at

ground idle resulted in a torching condition in which flames up to 10 feet in length were emitted from the tailpipe.

Attempts to accelerate out of this condition proved to be unsuccessful; the engine either flamed out or, as a precautionary measure, was shut down. Starts were then accomplished on JP-4 fuel, followed by a changeover to emulsified fuel at flight idle. No operational problems were encountered at power levels above flight idle. Several attempts were made to run at ground idle. In order to stabilize at ground idle, the engine was decelerated from power levels above flight idle to ground idle. Stable combustion occurred for approximately 15 seconds. After 15 seconds, long flames emerged from the tailpipe accompanied by muffled reports. Shortly thereafter, the engine flamed out or, as a precautionary measure, was shut down. After a shutdown of this nature, the engine could be started on the igniter fuel in the system, but operation could not be continued on main fuel. However, two immediate restarts were accomplished on emulsified fuel, and the engine was operated normally throughout the starting regime but had to be accelerated immediately to flight idle. In order to accomplish this, the engine was shut down from a level above 30-percent normal rated power; then it was immediately restarted. Normal restarts followed by a successful acceleration to flight idle had to be accomplished by using JP-4 fuel. The engine was operated for 6:34 hours on emulsified fuel. During this time, the engine was calibrated at various power levels. A substantial percentage of parameters of a 150-hour engine qualification program were explored.

During the testing, difficulty was experienced with the barrier-type filters in the T53-L-7 main fuel filter and the fuel control (Figures 46, 47, and 55). These filters became clogged with the fuel emulsion. (The T53-L-7 main fuel filter, which is engine-mounted on the turboprop engine, is similar to the airframe-mounted main fuel filter protecting the T53-L-11 engine.) The main fuel filter went into bypass after several minutes of operation at flight idle, at approximately 200 pounds per hour fuel flow. At one point during the test, it was necessary to replace the servo fuel filter before the engine could be accelerated beyond 70-percent gas producer speed (Figure 55).

Several transients were performed from flight idle to takeoff power. Transient attempts from ground idle were unsuccessful. Figure 56 depicts an acceleration from flight idle to takeoff power while using emulsified fuel. A comparison with Figure 54 shows that the acceleration while using JP-4 fuel is 4.3 seconds, compared with 4.8 seconds for emulsified fuel, which is approximately 11 percent slower. Since the fuel control schedules fuel rate on a weight basis, and since the emulsified fuel (97-percent emulsion) contains 4-percent water and chemical by weight, this



GAS PRODUCER SPEED, n_I, %
40 50 60 70 80 90 100
n_I, %
POWER TURBINE SPEED, n_{II}, %
20 30 40 50 60 70 80 90 100
n_{II}, %
4.3 SECONDS
ACCEL. TIME
95% POWER CHANGE
COMPRESSOR DISCHARGE
PRESSURE, P_{s4}, IN. HG.
0 20 40 60 80 100 120 140 160 180
P_{s4}, IN. HG.
FUEL FLOW, W_f, PPH

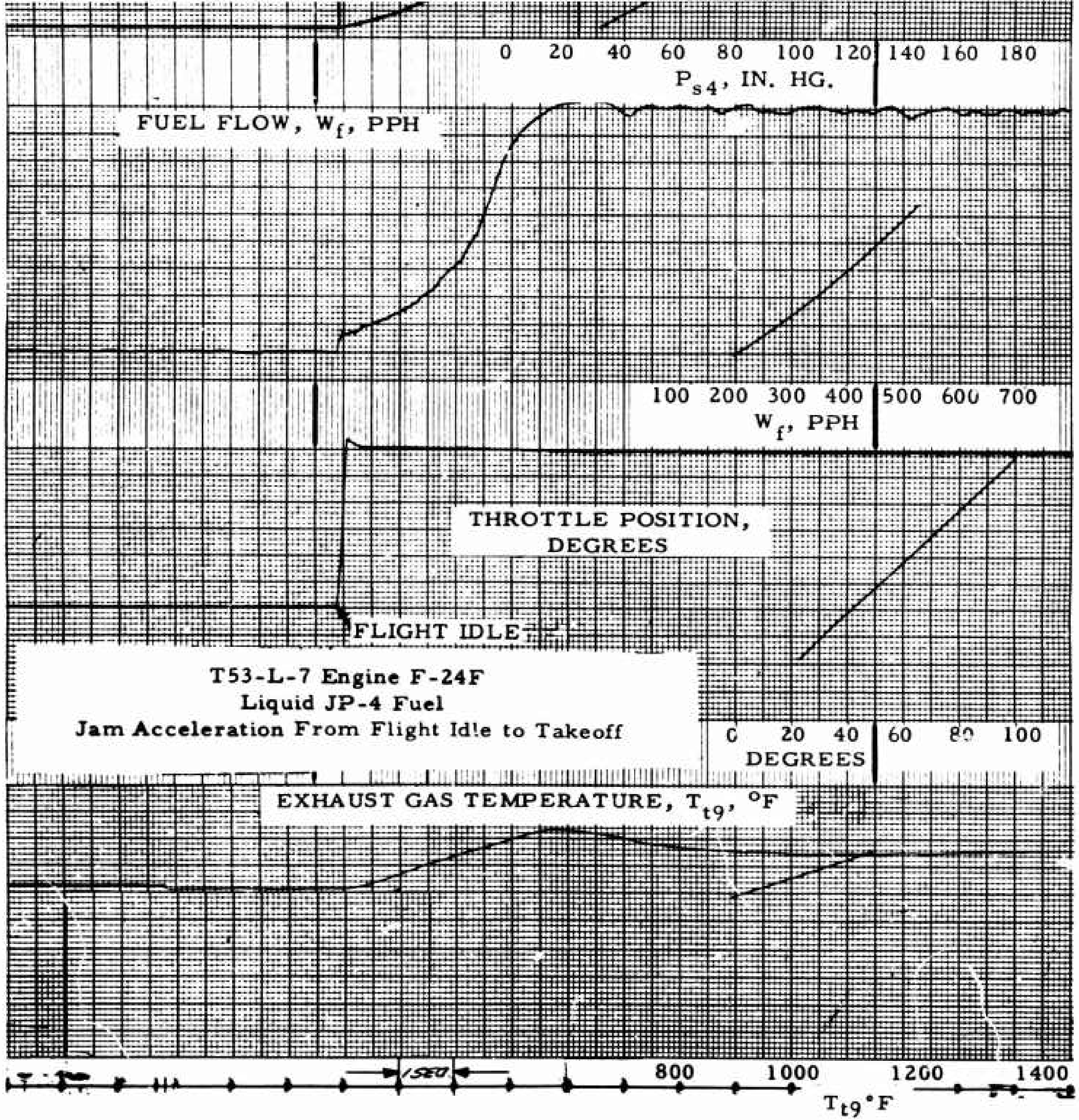


Figure 54. Sanborn Trace of Flight Idle to Takeoff Power Transient With JP-4 Fuel.

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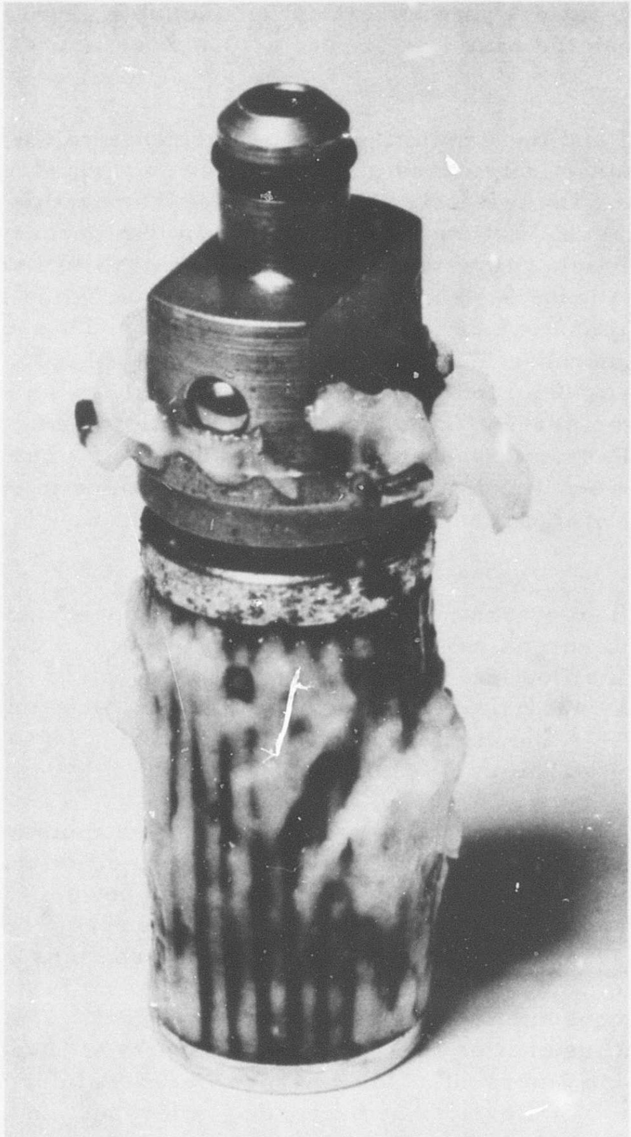


Figure 55. Fuel Control Servo Fuel Filter. (Note clogged condition with JD-1 fuel.)

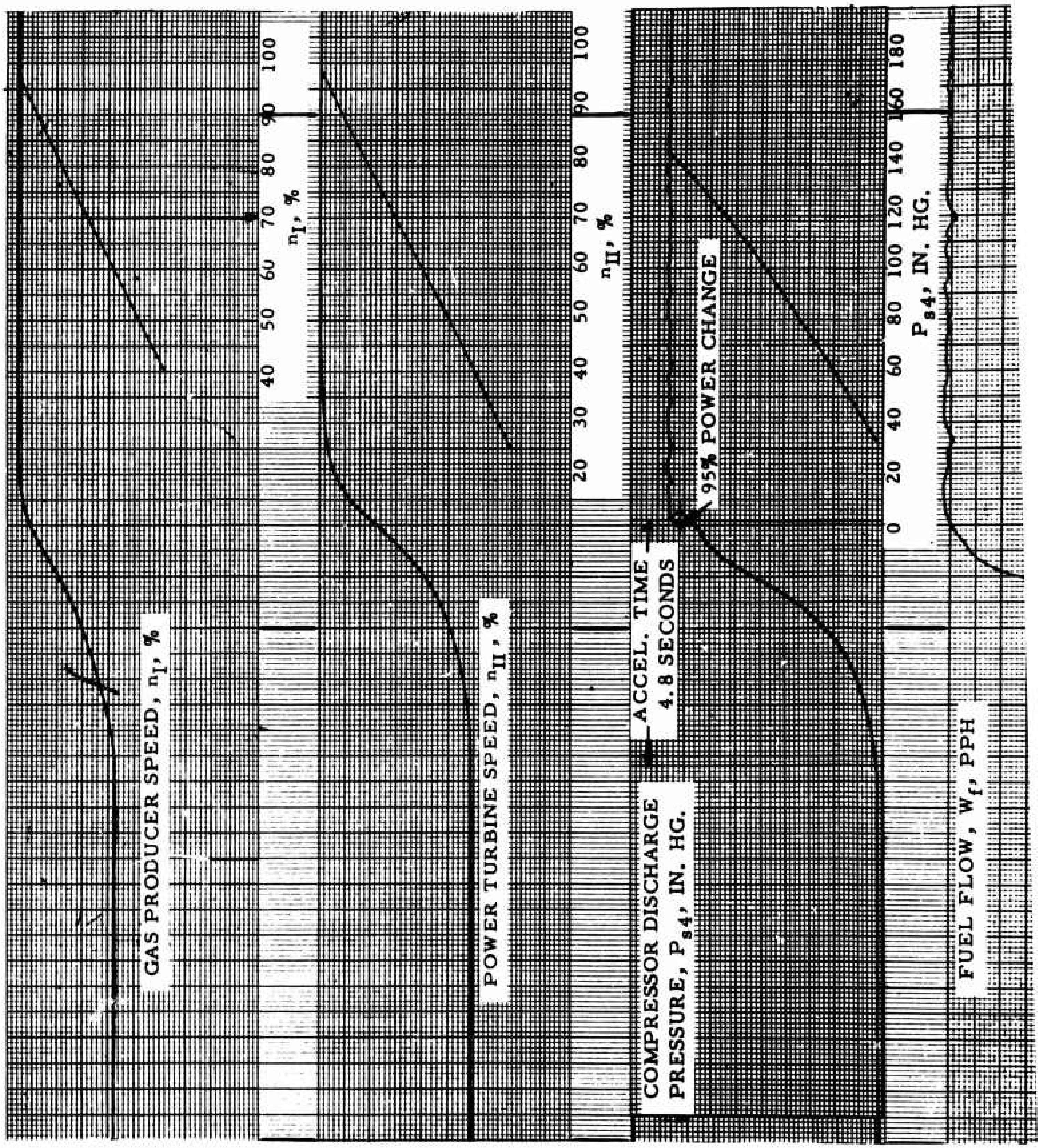
increase in acceleration time is predictable. In confirmation of this prediction, accelerations (in another test engine) with JP-4 scheduled 4 percent leaner than the base line showed a 10-percent increase in acceleration time.

The JP-4 fuel and the emulsified fuel performance calibrations showed no significant change in referred shaft horsepower versus referred gas producer speed for the two fuels. Turbine inlet temperature (T_{t5}) for the emulsified fuel calibration was calculated with 96 percent of the heating value of JP-4 fuel. Referred turbine inlet temperature versus gas producer speed (Figure 57) shows an increase of approximately 15°F in turbine inlet temperature for the emulsified fuel. This increase in T_{t5} is due to the increase in fuel rate (JP-4 content). Figure 58, referred fuel rate versus referred gas producer speed, shows an increase of between 5 and 6 percent in the emulsified fuel flow above that of JP-4 fuel. The plot of JP-4 contained in the emulsified fuel flow rate shows an increase of between 1 and 2 percent in JP-4 (contained in the emulsion). The accuracy of measurement in determining fuel flow is approximately 1 percent.

Referred airflow versus referred gas producer speed, and compressor pressure ratio versus referred gas producer speed, show no change between the emulsified fuel and the JP-4 fuel. Figure 59, referred shaft horsepower versus referred gas producer speed, shows little change between the JP-4 and emulsified fuel calibrations. The slight scatter in data is within the limits of accuracy.

A significant change was noted in specific fuel consumption when using emulsified fuel as compared with JP-4. The specific fuel consumption increased 6 percent at 50-percent normal rated power. At levels above 75-percent normal rated power, the increase in specific fuel consumption was 5 percent (Figure 60). Since the emulsion contains 4 percent by weight of water and chemical, which has little or no heating value, the specific fuel consumption was reduced by 4 percent. The increase in specific fuel consumption then becomes 2 percent at 50-percent normal rated power and 1 percent at levels above 75-percent normal rated power. This increase is believed to be partly due to a reduction in combustion efficiency at low power levels. While this correction for water content is thermodynamically correct, it is academic, since the specific range of the using aircraft must reflect a total fuel weight carried.

Figure 61, referred tailpipe temperature versus referred gas producer speed, shows a reduction of between 20° and 25°F in exhaust gas temperature when using emulsified fuel as compared with JP-4. This change could be a result of a temperature profile change at the T_{t9} location


GAS PRODUCER SPEED, n_I, %
40 50 60 70 80 90 100
n_I, %
POWER TURBINE SPEED, n_{II}, %
20 30 40 50 60 70 80 90 100
n_{II}, %
COMPRESSOR DISCHARGE PRESSURE, P_{s4}, IN. HG.
ACCEL. TIME 4.8 SECONDS
95% POWER CHANGE
0 20 40 60 80 100 120 140 160 180
P_{s4}, IN. HG.
FUEL FLOW, W_f, PPH

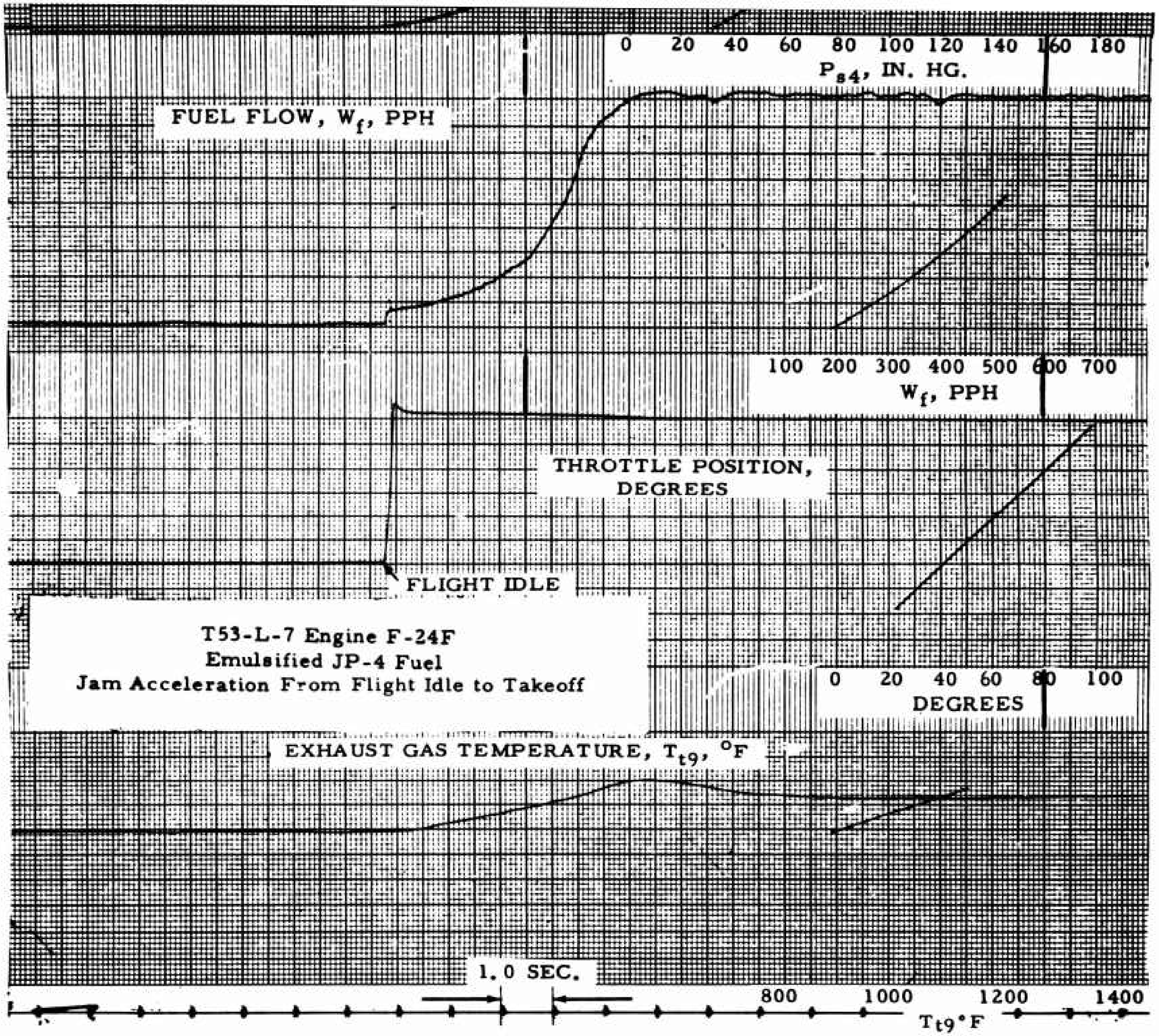


Figure 56. Sanborn Trace of Flight Idle to Takeoff Power Transient With JD-1 Fuel.

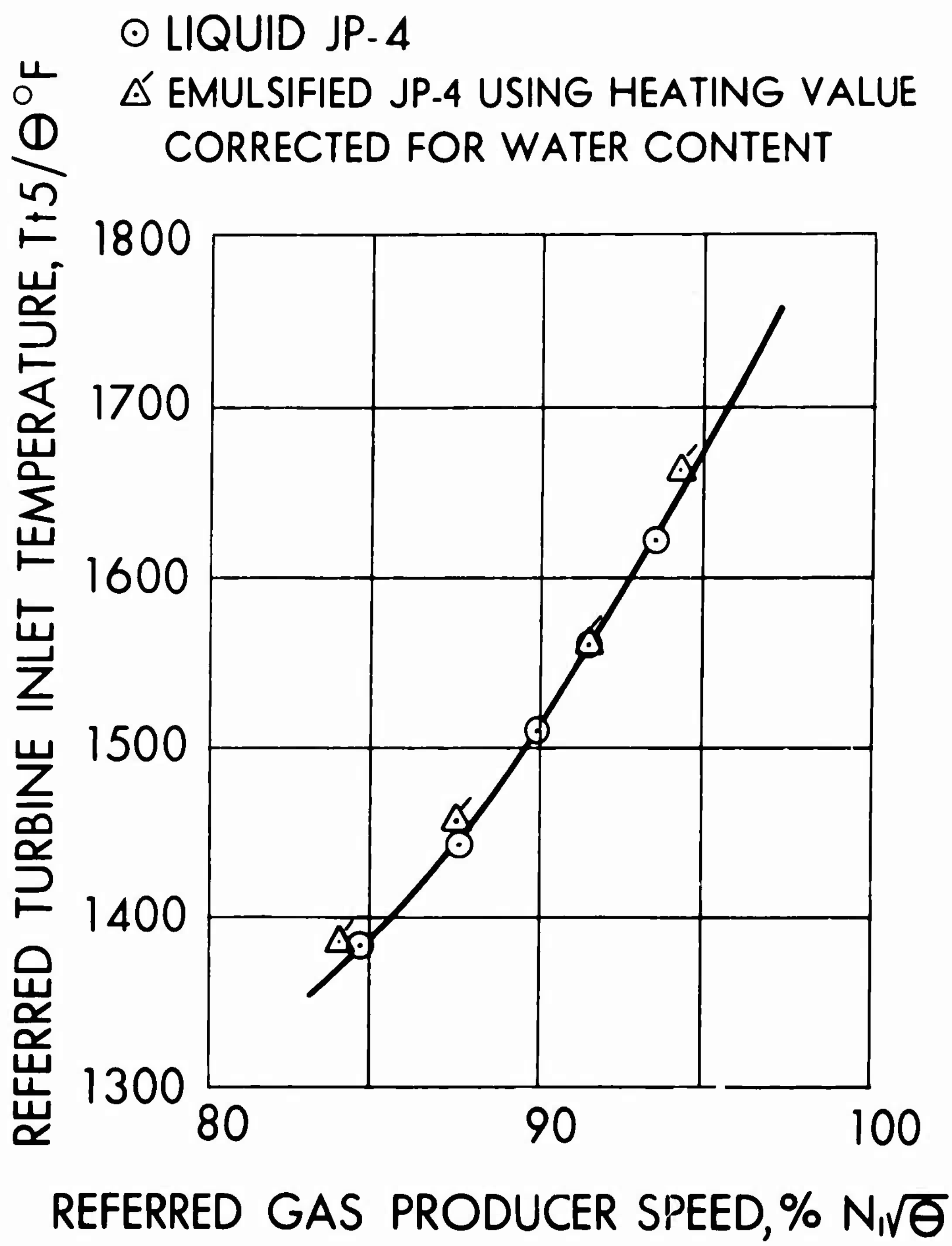


Figure 57. Referred Turbine Inlet Temperature Versus Gas Producer Speed.

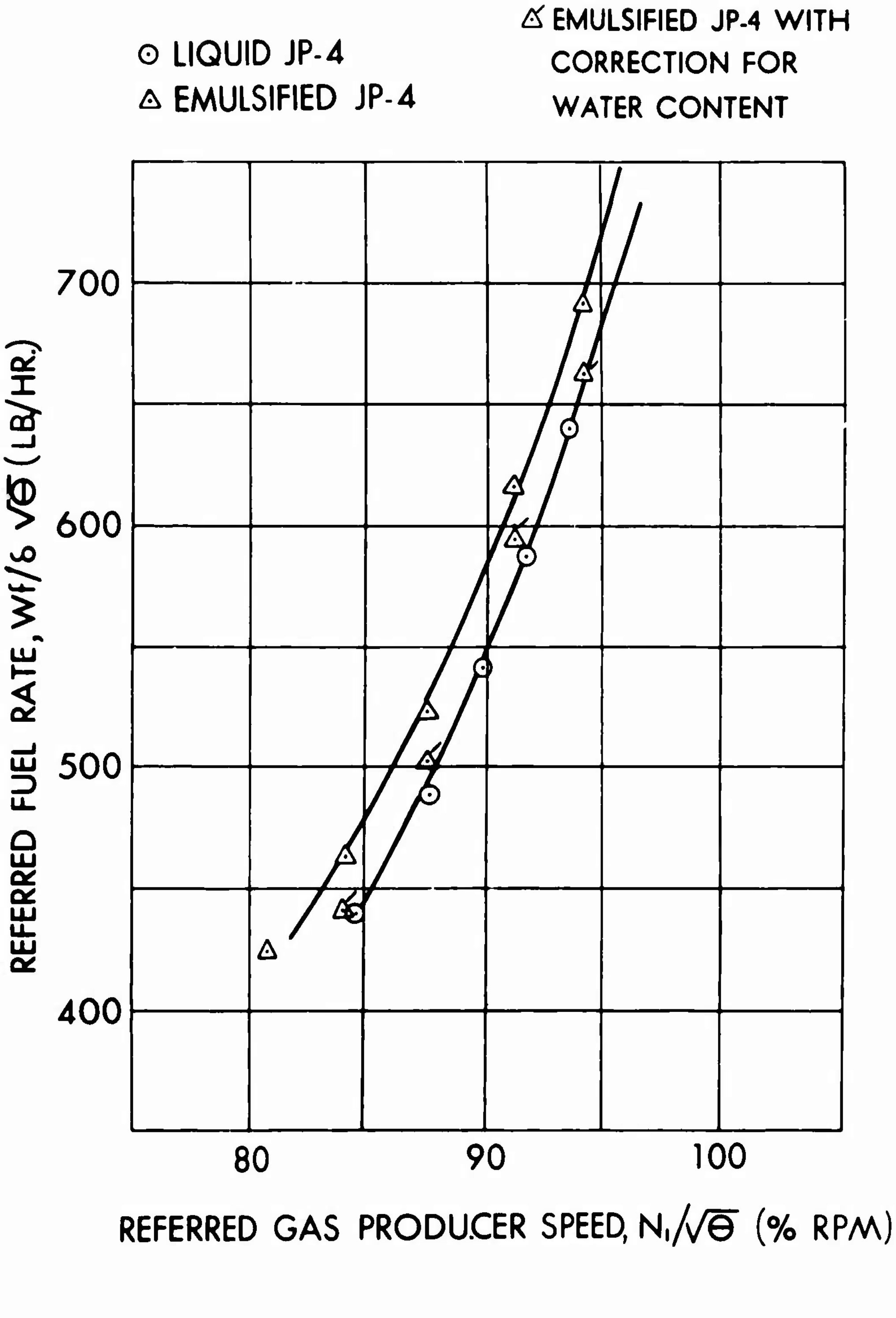


Figure 58. Referred Fuel Rate Versus Referred Gas Producer Speed.

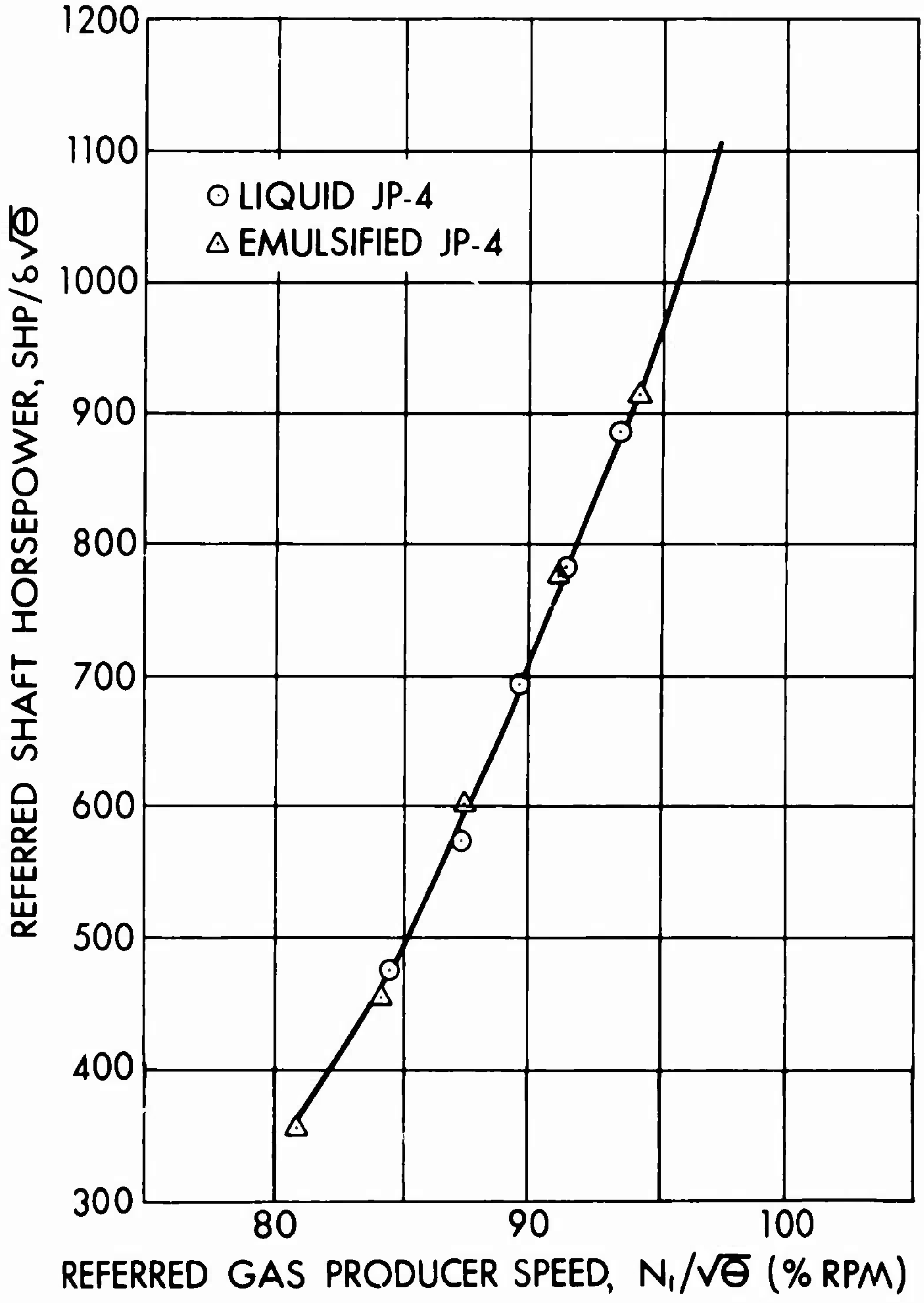


Figure 59. Referred Shaft Horsepower Versus Referred Gas Producer Speed.

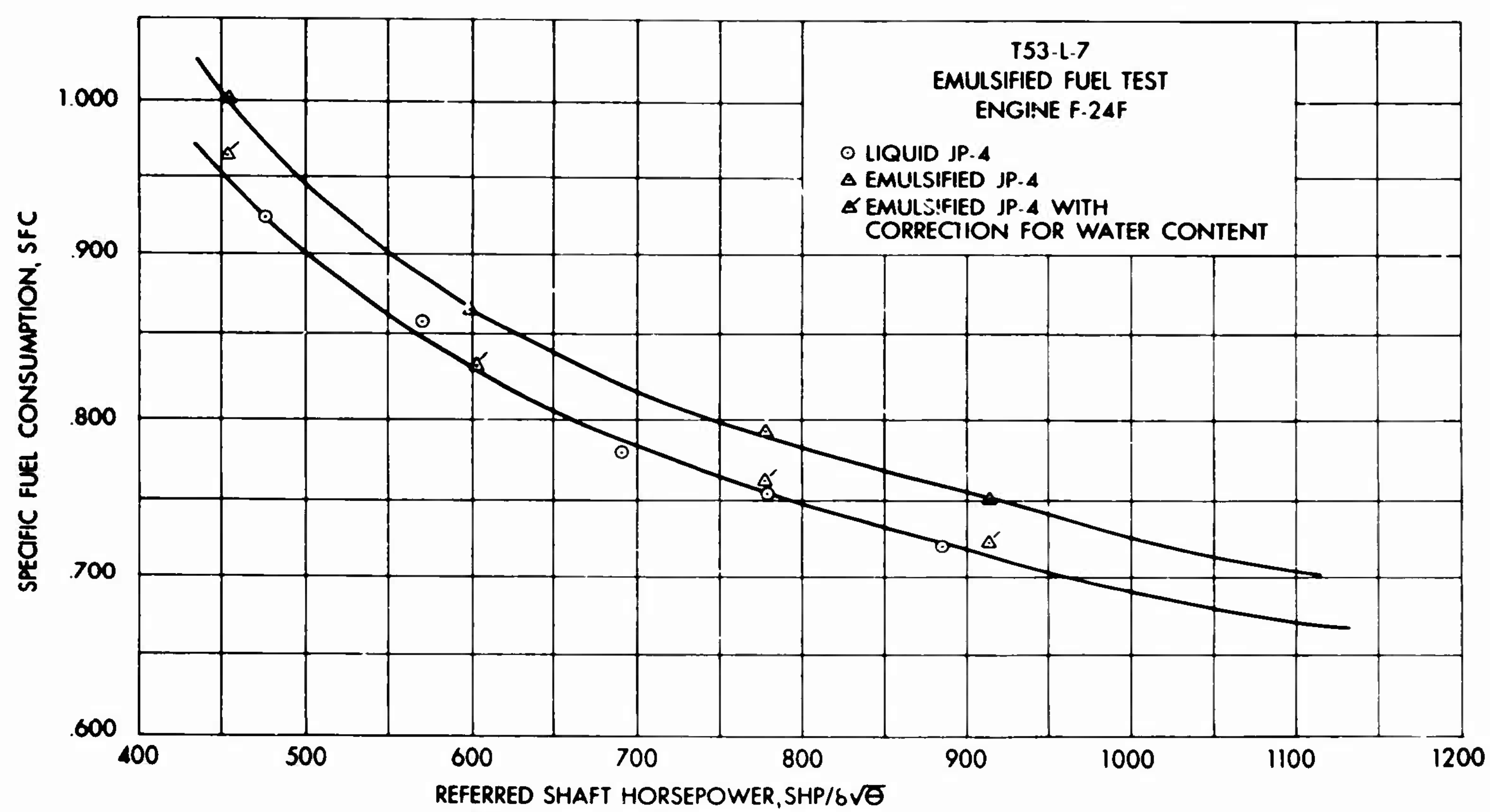


Figure 60. Specific Fuel Consumption Versus Referred Shaft Horsepower.

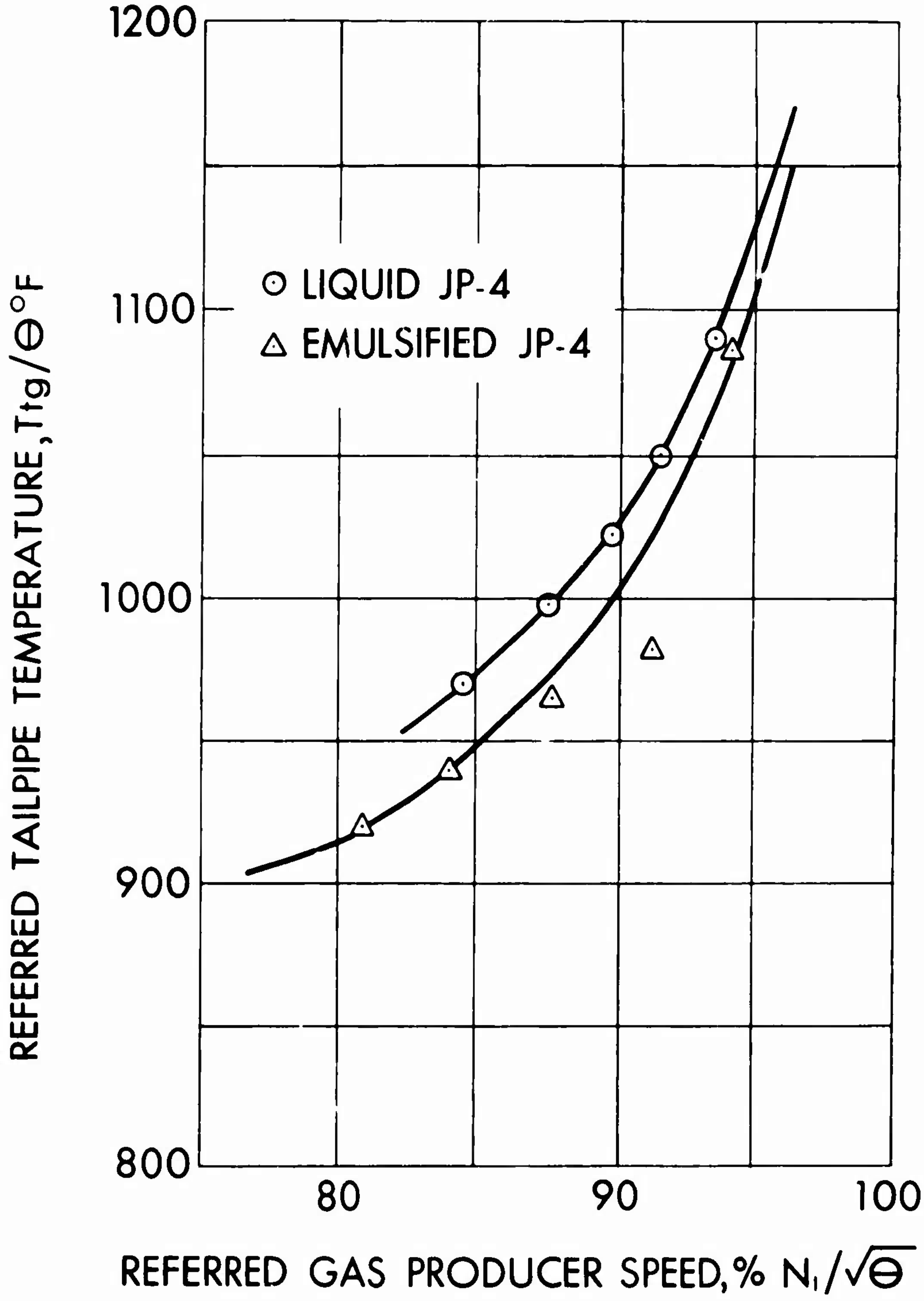


Figure 61. Referred Exhaust Gas Temperature Versus Referred Gas Producer Speed.

(lower reading on the averaging tailpipe harness). The 4 percent, by weight, water and chemical content adds additional cooling, which results in a lower T_{t9} reading. The extent of this reduction is not known.

POSTTEST INSPECTION

The condition of the combustor turbine section of the engine after completion of the test was good. The combustor liner had some moderate coke deposits on the baffle plates (Figures 62 and 63). These coke deposits are believed to have been caused by emulsified fuel (not in liquid form) deposited on the liner during attempts to run at ground idle. JP-4 deposits on liner baffles are usually in the form of soot. Diesel and leaded fuels have shown crater-like buildups in past engine operating experience. Emulsified fuel, compared with diesel and leaded fuels, was seen to produce coke buildup within a shorter period of engine operation. Inspection of the vaporizers showed considerable rusting of the fuel flow dividers. Inspection of the engine accessories showed corrosion problems similar to those encountered during Phase I testing.

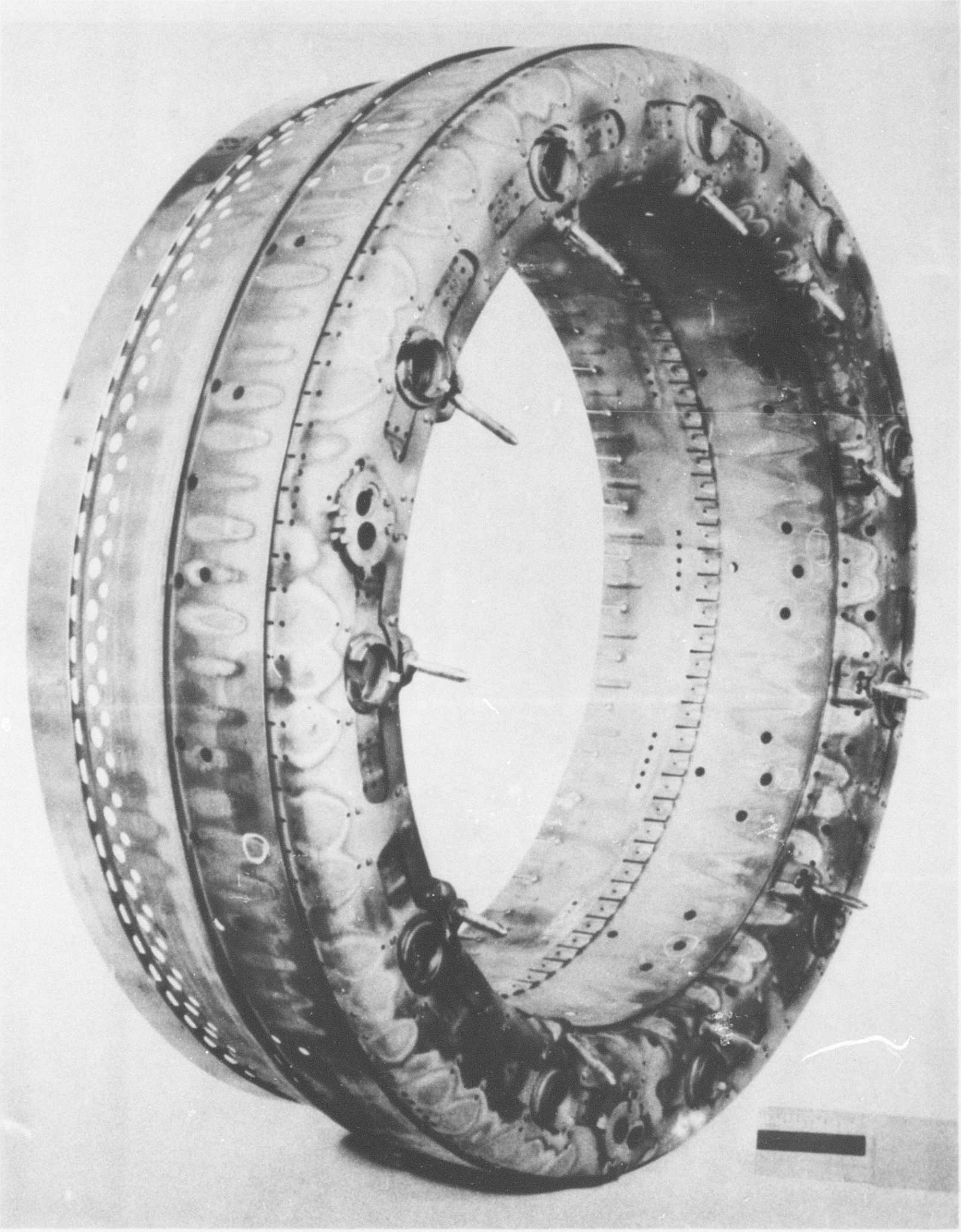


Figure 62. Vaporizing Combustor Liner; Overall View.

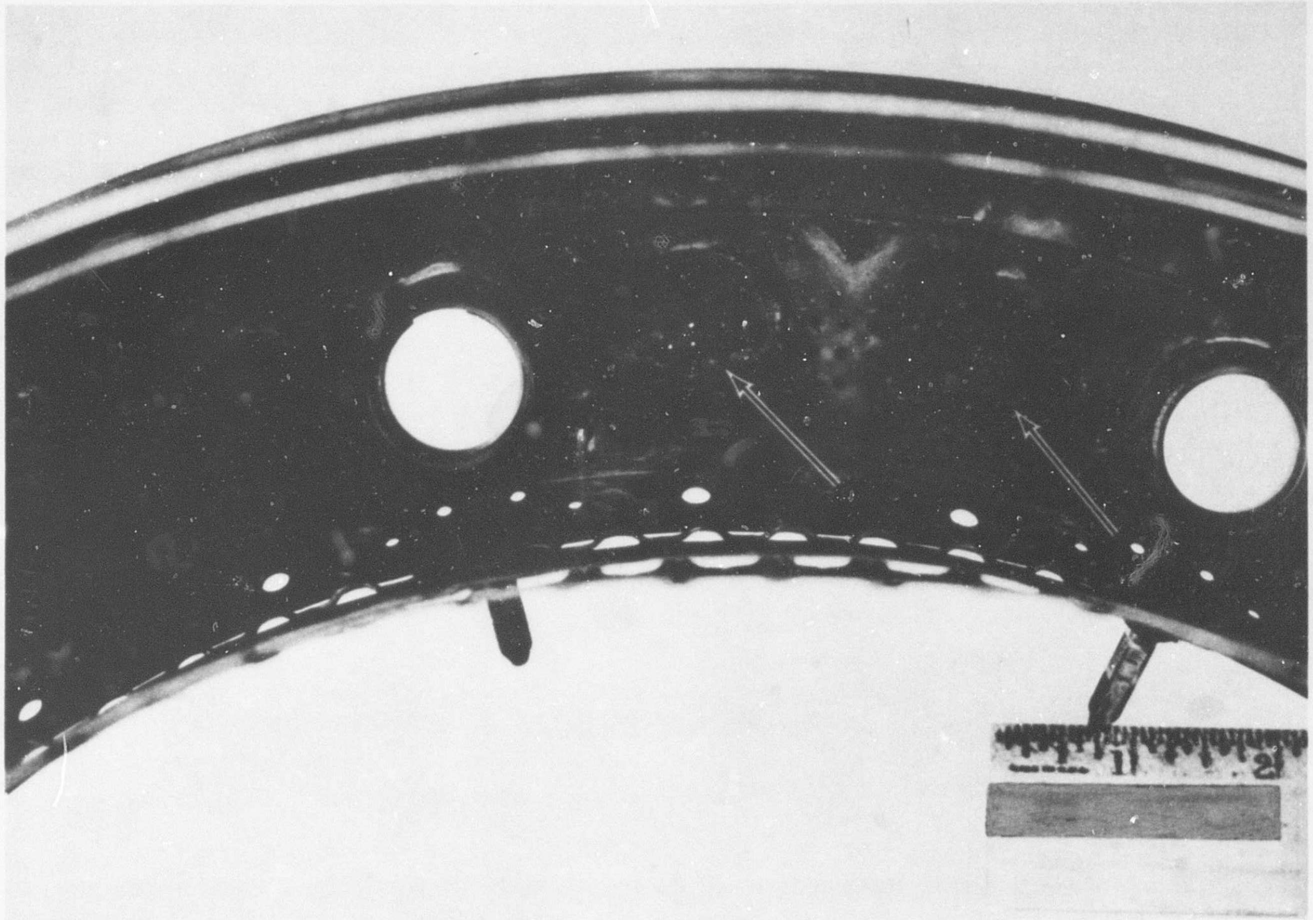


Figure 63. Combustor Liner Interior; Close-Up View. (Note coke deposits.)

CONCLUSIONS AND RECOMMENDATIONS

PHASE I - BENCH TEST

1. Fuel Control

It is concluded that:

a) The servo amplifier valves stick. The dense emulsified fuel packs around the valve stems, preventing liquid fuel from lubricating the "O" seals. Eventually the dry seals cause enough friction to cause sticking of the valves and subsequent seal failure.

b) Pressure regulation is unstable. The pressure differential across the main fuel metering valve should be held constant by the fuel pressure regulating valve. With emulsified fuel, the pressure differential fluctuates irregularly due either to the changing nature of the fuel or to the air entrapped behind the valve diaphragm.

c) Aluminum castings corrode. The fuel control housing and the computer housing assembly are susceptible to corrosion when subjected to JD-1 emulsified fuel. It is believed that this problem will occur with all emulsified fuels which use water and a detergent to enshroud the fuel.

It is recommended that:

a) Alternate servo amplifier valve seal designs be investigated in order to overcome seal wear and lubrication problems. It is possible that if a broken-down emulsion is delivered to the fuel control, the seal wear and lubrication problems might not exist.

b) Endurance testing of fuel controls be carried out to ascertain the long-range effects of emulsified fuel on a chemical and physical deterioration of internal control hardware. This endurance testing should be done with two fuel controls; one control should use emulsified fuel, and another control should use a completely broken-down emulsion.

c) The operation of the diaphragm-type pressure regulating valve be studied with emulsified fuel. The unstable pressure regulation problem should not exist with a completely broken-down emulsion.

2. Main Fuel Filter

It is concluded that:

a) The main fuel filter for the T53-L-7/11/13 engines is not acceptable for filtering of emulsified fuel due to the large pressure drop across the filter, which causes the filter to be in bypass above flight idle conditions.

b) The main fuel filter housing is susceptible to corrosion when subjected to JD-1 emulsified fuel.

c) The main fuel filter provides adequate filtration when filtering a broken-down emulsion.

It is recommended that:

a) The main fuel filter be redesigned in order to filter the emulsified fuel.

b) Endurance testing of the main fuel filter be carried out using a broken-down emulsion.

c) Corrosion of the main fuel filter housing be investigated with a broken-down fuel emulsion prior to initiating a material change to make it resistant to corrosion from emulsified fuels that are water enshrouded.

3. Accessories - Bypass Filter, Starting Fuel Solenoid Valve, Starting Nozzles, and Main Fuel Manifold

It is concluded that:

a) Fuel system accessories operation was satisfactory with JD-1 emulsified fuel.

b) The accessories are susceptible to corrosion when operated with JD-1 emulsified fuel.

It is recommended that:

a) Endurance testing of the fuel system components be carried out to ascertain the long-range effects of emulsified fuel.

b) Evaluation of the fuel system accessories be performed for all engine environmental test conditions when subjected to operation with emulsified fuel.

PHASE II - ENGINE TEST

It is concluded that:

1. Starts cannot be successfully accomplished with a cold (70°F) engine. Although two successful restarts were made, restarts with a hot engine, in general, could not be successfully accomplished.

2. Accelerations from flight idle to takeoff power are approximately 11 percent slower with emulsified fuel than with JP-4 fuel. The increase in acceleration time is due to the 4 percent, by weight, of water and chemical content in the emulsified fuel, which in effect leans out the acceleration schedule by 4 percent.

3. Engine performance showed a significant deterioration when the emulsified fuel was used. The increase in specific fuel consumption (6 percent at 50-percent normal rated power and 5 percent at levels above 75-percent normal rated power) is attributed to the 4-percent water and chemical content of the emulsified fuel and to the lower combustor efficiency.

4. Engine operation was satisfactory in the power regime from flight idle to takeoff power. Engine operation at ground idle could be accomplished only while the fuel manifold and vaporizers were hot, thereby insuring liquid fuel at vaporizer entry.

5. Previous testing of a T53-L-11 engine using a T53-L-13 atomizing combustor showed the atomizing combustor to be more compatible than the vaporizing combustor with emulsified fuel.

It is recommended that:

1. A more extensive engine performance evaluation be made to compare the performance of a vaporizing combustor and an atomizing combustor.

2. Environmental limitations on starting be determined with emulsified fuel and compared with those of a broken-down emulsion.

3. Endurance and performance testing of an engine be accomplished to determine whether a broken-down emulsion (prior to the fuel control) is more compatible with existing gas turbine engines.

4. Engine testing be accomplished for all environmental conditions and the modifications required to operate an engine at these conditions be determined.

5. A noncorrosive emulsion be developed.

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PART 4. LYCOMING, T-55

by
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Contract DA 44-177-AMC-457(T)

INTRODUCTION

BACKGROUND

Aircraft fatalities and equipment loss which result from postcrash fires, rather than from the crash itself, have stimulated investigation into means of reducing the fire hazard in aircraft accidents. This research has indicated that emulsified fuel is a promising solution to this problem. In the emulsified, semisolid state, JP-4 fuel is more easily contained in the event of fuel tank rupture, vaporizes at a slower rate, and, if ignited, burns more slowly. These characteristics of emulsified JP-4 fuel reduce the threat from small arms fire and, in addition, minimize the danger of postcrash fire in survivable-type aircraft accidents. Several practical means of emulsifying JP-4 fuel have been developed. The objective of the subject program is to determine the feasibility of burning such an emulsified fuel in a T55 gas turbine engine incorporating an atomizing combustor.

RELATED EXPERIENCE

Prior to the work under the subject contract, Avco Lycoming Division conducted an evaluation of emulsified fuel in a T53-L-11 engine using a T53-L-13 atomizing combustor. Two emulsions were evaluated: the 97-percent emulsion (JD-1) of the Western Company, which was the fuel used in this program, and a 97.5-percent emulsion (EF4-101) developed by Petrolite Corporation. Limited running time on these two fuels demonstrated successful engine operation and indicated compatibility of the emulsified fuel with atomizing combustor operation.

The evaluation reported herein concerns the operation of a T55 engine, also with an atomizing combustor. Under a related contract, DA 44-177-AMC-453(T), operation of a T53 engine with a vaporizing-type combustor on emulsified fuel has been evaluated concurrently with the T55 engine evaluation.

PROGRAM ORIENTATION

The overall objective of this program is to determine the feasibility of burning emulsified fuels in a T55 turbine engine with atomizing combustor.

Phase I of this evaluation consisted of a bench test of the T55 fuel system for atomizing combustor engines, consisting of barrier fuel filter and boost pump, fuel control, fuel/oil heat exchanger, flow distributor valve, and fuel nozzle simulators. Flow rates with emulsified fuel were compared with the rates obtained on calibrating fluid in various conditions of fuel control operation. A 97-percent fuel emulsion was used.

In Phase II, a T55 turbine engine, with an atomizing combustor and the fuel system described above, was installed in a test stand. The operation of the complete engine on the emulsified fuel was evaluated and compared with the operation on JP-4 fuel.

FUEL EMULSIFICATION

JD-1 emulsified fuel was prepared by using a detergent formula developed by the Western Company of Dallas, Texas. To make 50 gallons of 97-percent emulsion, a mixture of 0.5 percent (0.25 gallon) of Western MFE-11, 2.5 percent (1.25 gallons) of water, and 48.5 gallons of JP-4 was used. The emulsion was prepared in a Western Company emulsifying and pumping console. The emulsifying portion of the console (Figure 64) consists of a 55-gallon stainless steel tank to contain the fuel and a Roper gear pump to cycle the fuel and to provide the shear needed for emulsification. The pump is driven through a Gerbing variable-speed drive by an explosion-proof, 2-horsepower, 220-volt, alternating-current, 3-phase motor. The pumping portion of the console (Figure 65), which was used to deliver fuel for engine and bench tests, consists of two 55-gallon stainless steel drums with air-powered piston pumps. The outlets of the pumps were connected to valving which allowed fuel to be pumped from either or both drums. From the valve, the fuel passed through a check valve, an accumulator, a fluid pressure regulator, and a 100-micron filtration system. Pressure gages are provided to indicate fluid output pressure (0-100 psi) and accumulator pressure (0-400 psi).

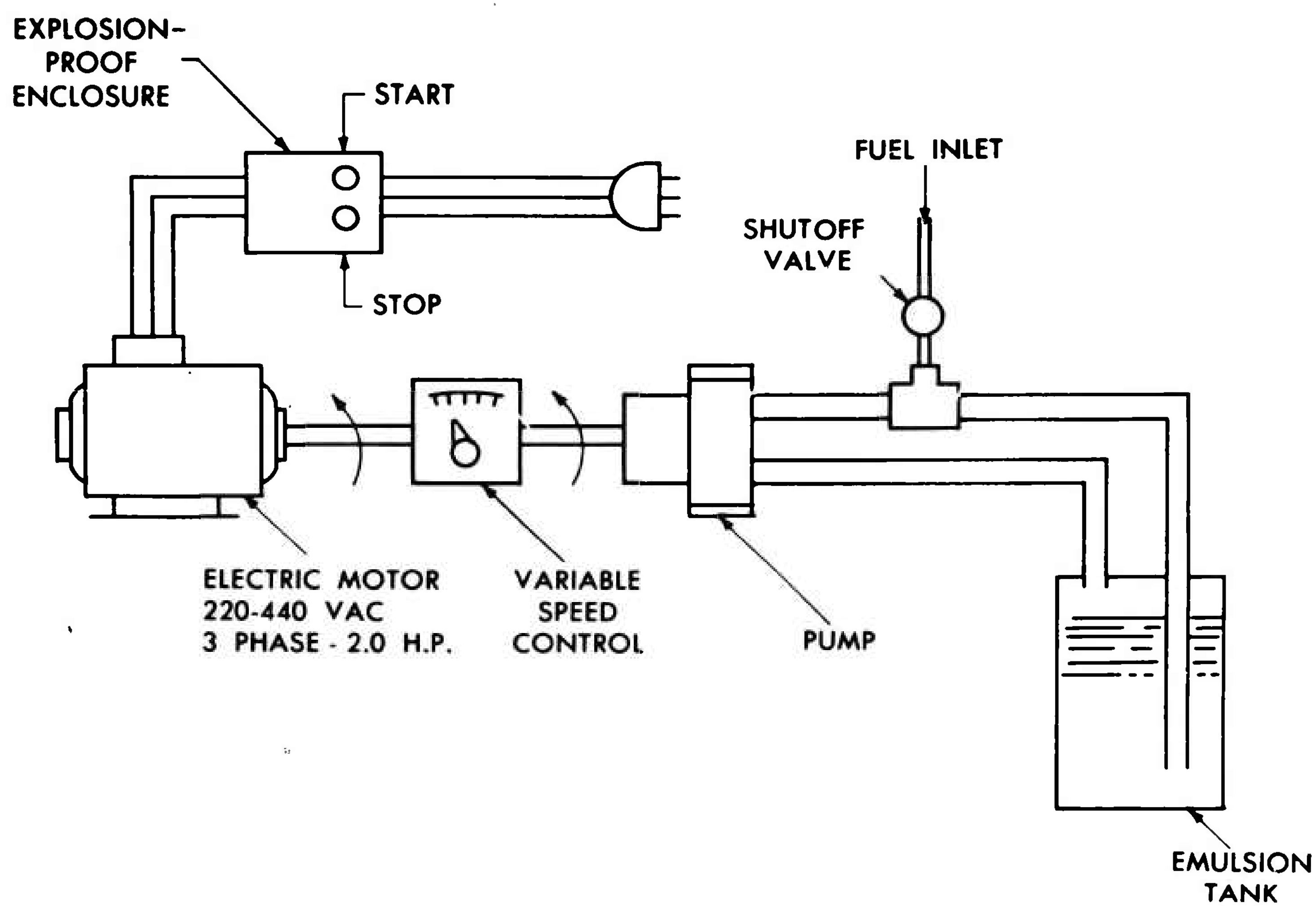


Figure 64. Western Company Emulsifying Schematic.

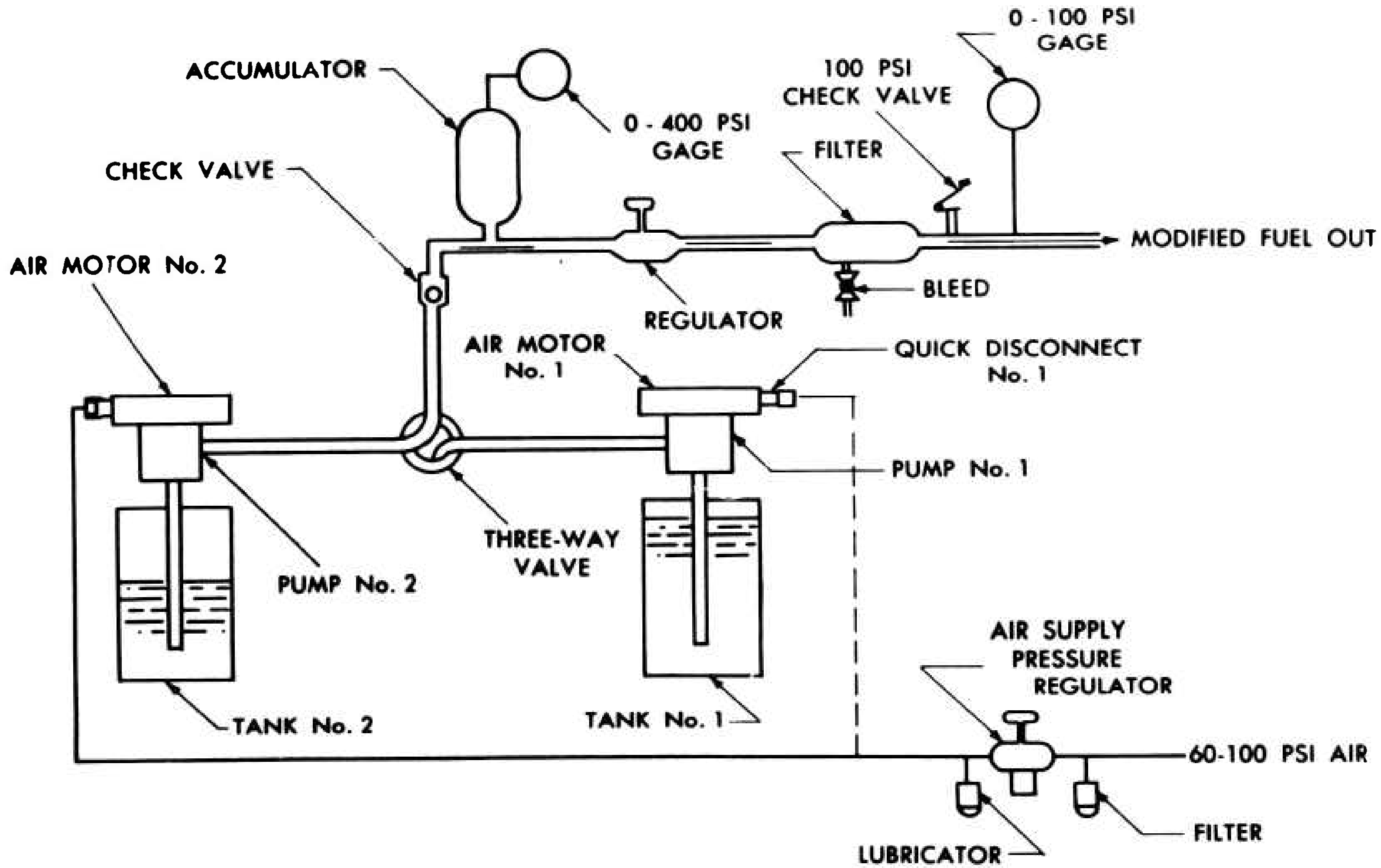


Figure 65. Modified Fuel Pumping Schematic of Western Company Emulsifying and Pumping Rig.

BENCH TEST

DESCRIPTION OF TEST ITEMS

A complete T55 atomizing combustor fuel system was installed on the laboratory fuel flow bench. Figure 66 shows a schematic diagram of this system, which consists of the following items:

1. Boost Pump, P/N 2-160-790-04, S/N 8. This is a centrifugal pump used to overcome the pressure drop of the barrier filter.

2. Barrier Filter, P/N 2-300-136-01, S/N 13. The main fuel filter is of the disposable cartridge type.

3. Fuel Control, P/N 2-160-620-09, S/N 25286. This is the Hamilton Standard JFC-31-9 control of the hydromechanical type which utilizes the fluid being pumped to actuate its servos. The control senses engine inlet temperature and pressure, gas producer (n_I) and power turbine (n_{II}) speeds, and compressor discharge pressure (P_3) to maintain the desired power level or power turbine speed and to schedule the fuel flow for starting, accelerating, and decelerating under varying temperatures and pressures.

4. Starting solenoid valve, P/N 2-300-191-02, S/N 4902. Actuation of this valve during starting admits unmetered fuel to the primer nozzles in the combustor.

5. Fuel/Oil Heat Exchanger, P/N 2-150-770-01 , S/N 439. Engine oil is cooled by passing through this heat exchanger, where heat is given up to the fuel.

6. Distributor Valve, P/N 2161-170-01, S/N 13. This valve divides the fuel flow between the primary and secondary manifolds to optimize fuel atomization.

7. The fuel nozzles were simulated by two orifices representing the total flow area of all primary and secondary nozzles.

The emulsified fuel delivery system was as described in the Introduction. Emulsified fuel flow was measured by the weight/time method.

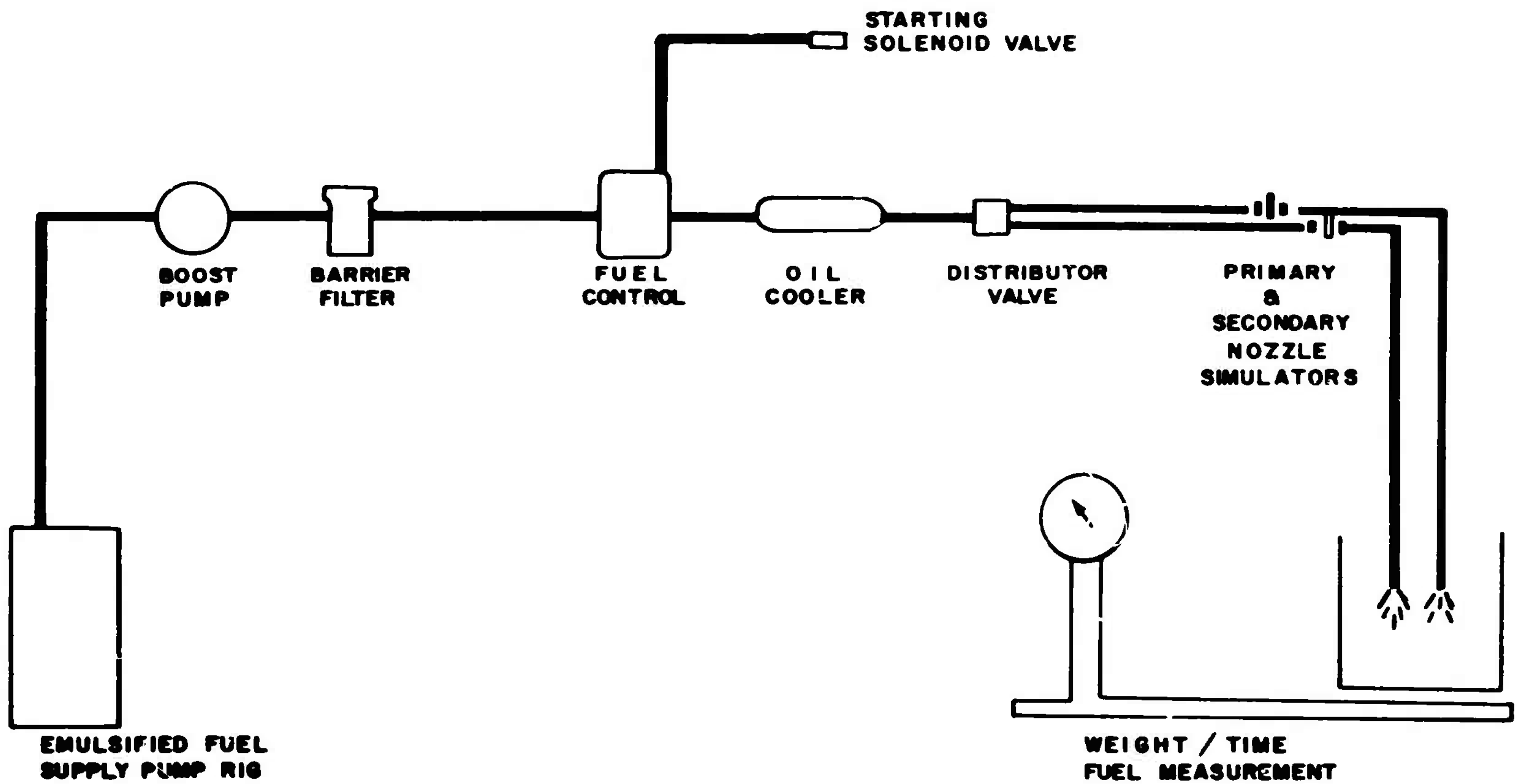


Figure 56. Schematic of T55 Fuel System for Atomizing Combustor.
Diagram shows bench test installation.

TEST DESCRIPTION

A modified calibration of the fuel system was conducted with MIL-F-7024A Type II calibrating fluid for base-line data. The same calibration points were recorded using the emulsified fuel. The inlet conditions to the fuel system were regulated to maintain approximately 25 psi to the boost pump inlet. The heat exchanger was not plumbed on the oil side; oil inlet and outlet on the heat exchanger were open to the atmosphere. A total of 400 gallons of the emulsified fuel was pumped through the control during the 2-hour calibration. The control was exposed to the emulsion for 72 hours. Upon completion of the test, the control was disassembled for inspection and photographs.

Comparative flows for MIL-E-7024A Type II fluid and the emulsified fuel for various control functions are shown in Table III. The data for the emulsified fuel are shown plotted against nominal schedules in Figure 67.

The fuel control was considered to be within normal calibration standards and capable of metering the emulsified fuel. The pressure drop across the barrier filter indicated that the unit was in full bypass above 10 percent n_I and, therefore, did not offer any protection for the balance of the fuel system. Figure 68 shows the filter completely covered by the emulsion. The emulsified fuel console pump to the fuel system generated rust and scale from within and delivered this contaminant to the fuel system. The emulsion as it discharged from the console pump was not homogeneous, and it appeared to be partially broken down to approximately 30- to 40-percent liquid JP-4.

The heat exchanger had a 3- to 5-psi increase in pressure drop versus fuel flow with the emulsion (Figure 69).

It appeared from this bench test that the fuel system would be capable of delivering and metering the emulsified fuel provided that it received clean supply fuel.

POSTTEST INSPECTION

The fuel control was disassembled for inspection, and the computer cavity was found to be completely filled with the emulsion (Figure 70). Evidence of a chemical reaction between the control parts and the emulsion appeared as oxidized areas on both the stainless steel computer linkage and the aluminum housing. A description of this condition after the engine test phase, with pertinent photographs, will be found under "Engine Test". Excessive rust particles were found in the computer cavity and servo passages. The control was flushed with water and calibration fluid, assembled, and made ready for engine testing.

TABLE III

MODIFIED FUEL CONTROL CALIBRATION FOR EMULSIFIED FUEL BENCH TEST

Fuel Temp (°F)	n_I (rpm)	Fuel Flow (W_f, lb/hr)		Gas Producer Power Lever	Schedules
		MIL-F-7024-A	JD-I		
75 ± 10	420	120	110	Military	Start
75 ± 10	600	130	140	Military	Start
75 ± 10	1000	250	284	Military	Acceleration
75 ± 10	2000	516	520	Military	Acceleration
75 ± 10	2550	585	555	Military	Acceleration
75 ± 10	3100	1032	1020	Military	Acceleration
75 ± 10	4000	1500	1326	Military	Military Droop
75 ± 10	1700	210	180	Ground Idle	Ground Idle Droop
75 ± 10	400	67	98	Ground Idle	Ignitor

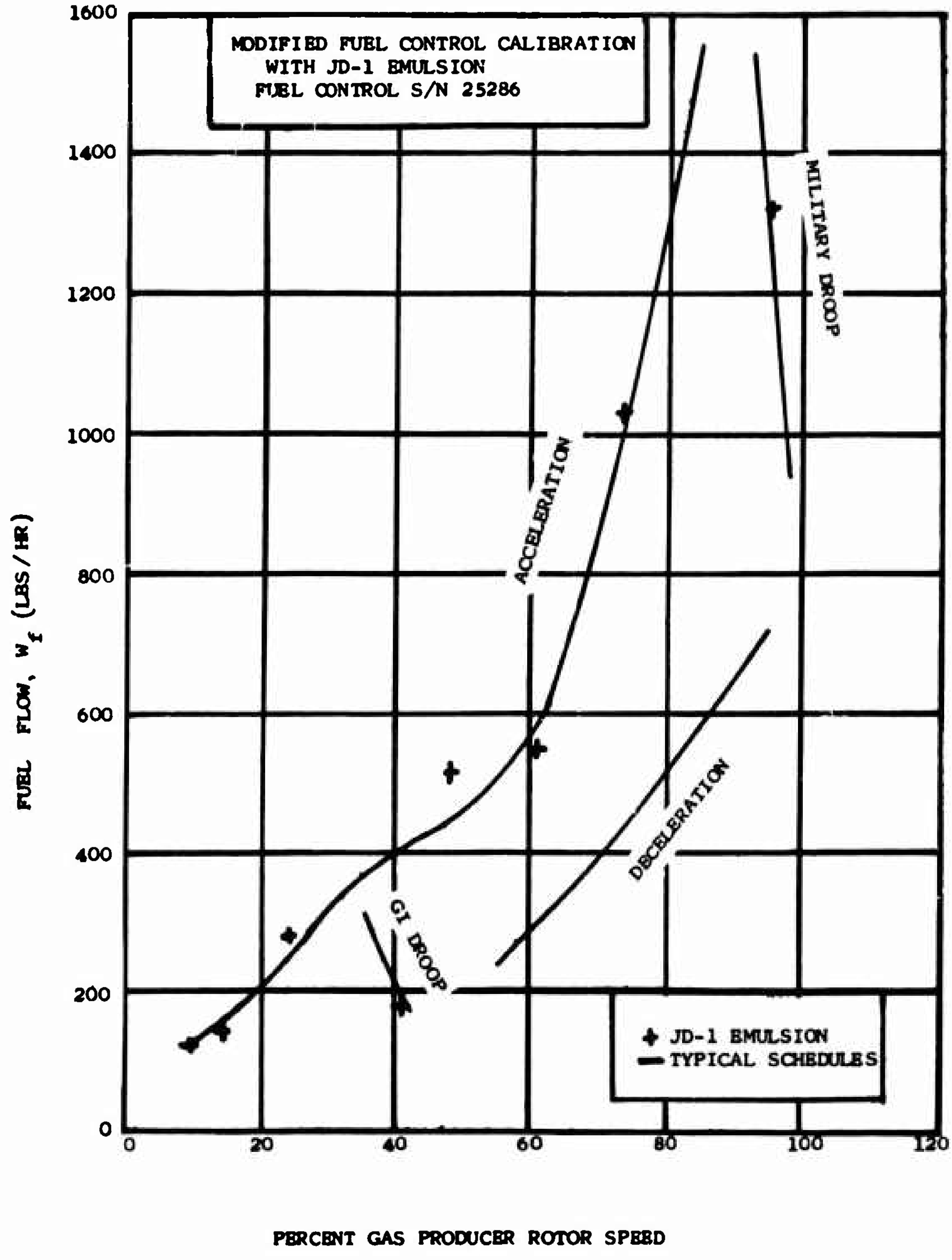


Figure 67. Bench Calibration of Fuel System With Emulsified Fuel Compared to Nominal Values.

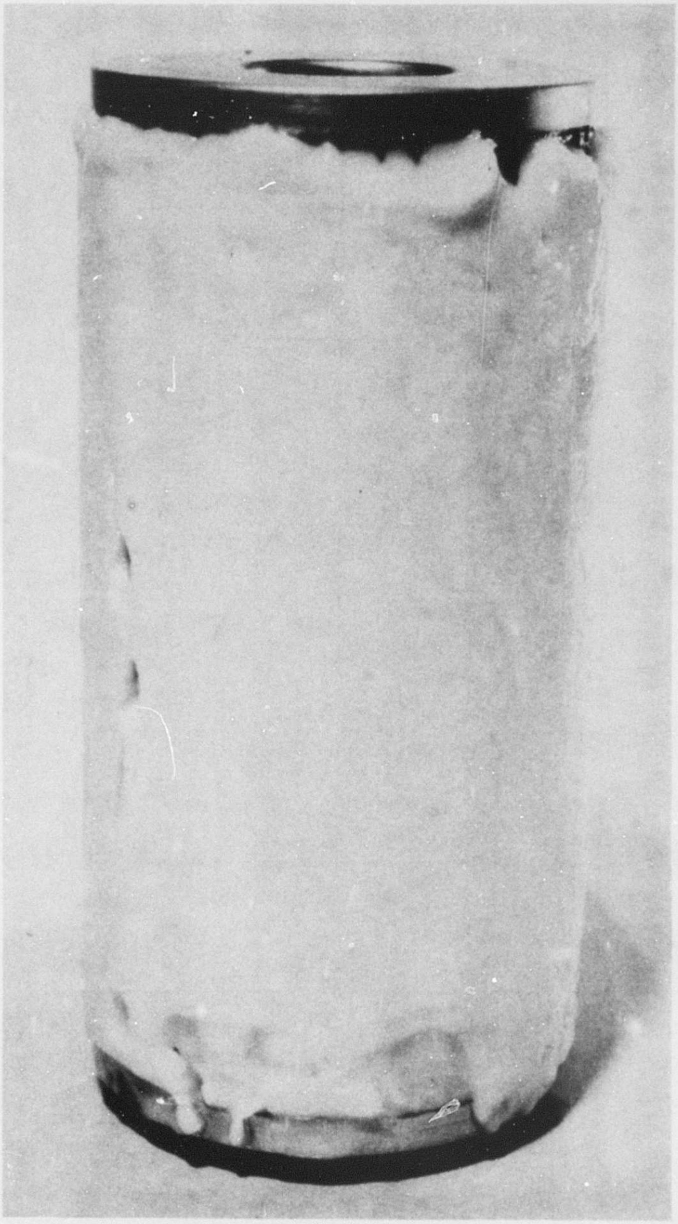


Figure 68. Fuel Filter Completely Clogged With Emulsified Fuel.

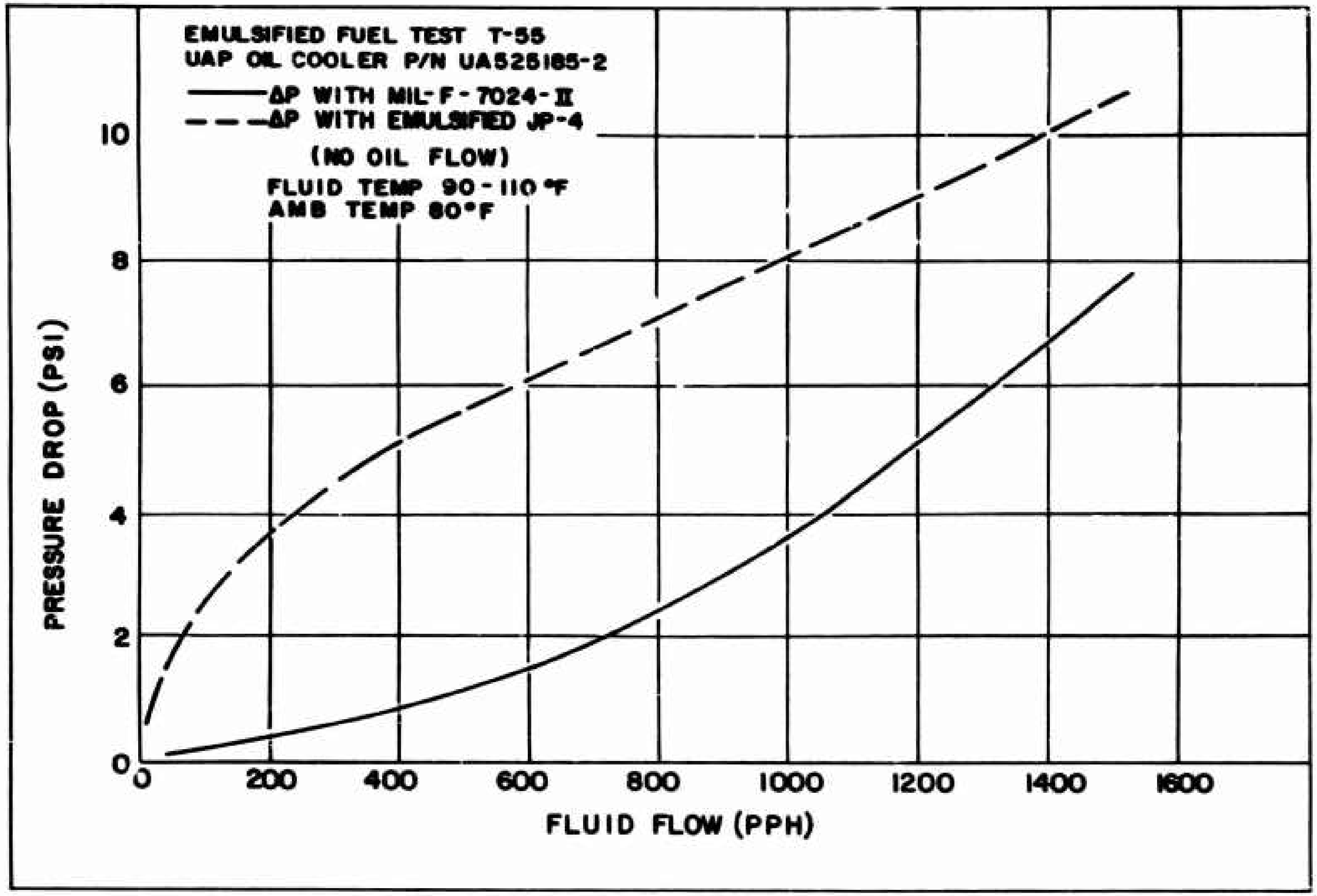


Figure 69. Oil Cooler Pressure Drop Versus Fuel Flow for JP-4 and Emulsified Fuel.

Figure 70. Fuel Control Showing Computer Cavity Completely Filled With Emulsified Fuel After Bench Test.

ENGINE TEST

ENGINE DESCRIPTION

T55-L-7 Engine 37 used for this test was of standard configuration except for the combustor. Instead of the vaporizing combustor currently in production, an atomizing combustor now under development was used. This combustor is of the annular, reverse-flow type having 28 atomizing nozzles. These are of the dual-orifice type, which uses the small primary orifices at low flow, during starting, and the secondary, larger orifices, in addition, in the remainder of the fuel flow range.

The remainder of the fuel system was as described in "Bench Test" and was, in fact, composed of the identical items.

INSTRUMENTATION

The engine was installed for the test in the outdoor test stand. Power absorption was by means of a water-brake which was supported from the engine on front strain-gaged beams which sense output torque. Standard test cell instrumentation was used to measure the following engine variables:

1. Airflow

   An inlet nozzle with ASME-recommended geometry utilizing throat static and total pressures.

2. Rotor Speeds

   Standard Electric Time Corporation tachometers electrically driven by MS 28054 tachometer generators.

3. Pressures

   Calibrated manometers and Bourdon tube gages.

4. Temperatures

   Self-balancing precision Brown potentiometers for indicating high and low temperatures as sensed by chromel-alumel and iron-constantan thermocouples, respectively.

5. Vibration

Consolidated Engineering Corporation miniature vibration pickups and vibration meter with a 70-cps high-pass filter.

A Sanborn recording oscillograph was used to record transient measurements of gas producer and power turbine rotor speeds, compressor discharge pressure, primary and secondary manifold pressures, and exhaust gas temperature. A Cox turbine flow element was used for flow measurement of the JP-4 fuel. This element was installed downstream of the fuel/oil heat exchanger so that it could also be used when operating with emulsified fuel when the temperature of the fuel out of the heat exchanger was hot enough to liquify the fuel. A filter with no bypass was installed ahead of this element to protect it, since it was expected that the emulsion would cause upstream filters to operate on bypass. A linear mass flowmeter was installed for primary measurement of emulsified fuel flow. The fuel supply drums were mounted on scales to provide a supplementary fuel measurement system.

JP-4 fuel was provided by the Lycoming test facility tank and pumping systems. Emulsified fuel was supplied from two 55-gallon stainless steel drums and the emulsified fuel pumping facilities described in the Introduction.

TEST DESCRIPTION

An initial calibration of steady-state performance and transients was performed on JP-4 fuel. A repeat of this calibration on emulsified fuel was intended, but this was not entirely possible because of difficulties which will be described below.

During the initial calibration on JP-4 fuel, the fuel control was adjusted to give typical starts and acceleration times. Following this calibration, the engine was started on JP-4 fuel, and a changeover was made to emulsified fuel while operating the engine at flight idle. The engine was operated successfully on the emulsified fuel for 30 minutes at low powers. Data readings were taken at 70-percent and 60-percent gas producer speed. While decelerating towards ground idle, the engine flamed out at 50-percent gas producer speed. At the time, it was thought that the filter protecting the fuel flowmeter element had clogged, limiting the flow of fuel to the manifold. A manual bypass around the filter and flow element was then installed so that the fuel would flow through these items only when a measurement was necessary. The emulsified fuel was not removed from the engine fuel system, and no attempt to

restart the engine was made until a weekend had elapsed.

Several start attempts were then unsuccessful, and it was found that the control was delivering no main (metered) fuel during cranking, although there was primer (unmetered) fuel. The fuel control was removed from the engine and was run on the flow bench, at a higher speed than is possible when cranking the engine, while being flushed with water. This cleansed the control, and starts (on JP-4 fuel) were again possible.

While investigating the failure to start, it became evident that a hole existed between the fuel and oil sides of the heat exchanger. Investigation showed a hole in one of the cooler tubes which appeared to be similar to previous failures caused by brazing flux left in the heat exchanger during manufacturing. It was concluded that the failure was not a direct result of using emulsified fuel, but that the presence of water in the fuel may have accelerated the corrosion.

After the control had been flushed, the engine was started on JP-4 fuel. The changeover to emulsified fuel was made at 80-percent gas producer speed. After 20 minutes, the engine flamed out when the supply pump failed to deliver fuel to the engine. Starting problems were again encountered. Flushing the control provided only temporary relief. Blocking open the fuel control foot valve, which prevents fuel from being delivered before pump pressure reaches approximately 110 psi, did not provide any substantial improvement. Only three additional minutes of running on emulsified fuel were obtained before the control was returned to the laboratory for disassembly. No one component causing the malfunction was discovered, but emulsified fuel was found to be packed in many areas of the control.

The control was flushed, reassembled, and returned to the engine. The pump filter and control main filter were removed at this time, since it was assumed that filtration was already ineffective because of open bypasses, and it was desired to reduce pressure drop even further. Engine operation on liquid fuel was found to be satisfactory. After a start on JP-4 fuel, a changeover to emulsified fuel was made at 80-percent gas producer speed, and the engine was operated for 35 minutes at fuel rates of approximately 750 to 900 pounds per hour. At this time, moving the power lever towards a lower power setting caused the engine to flame out at 75-percent gas producer speed. A restart was not possible until the pressure regulating valve was removed from the control and the emulsion cleaned from the passages in the valve.

It was possible to accumulate running time on the emulsified fuel only by cleaning out the pressure regulating valve after approximately every 100 gallons of emulsified fuel consumed. This amount of fuel gave approximately 30 to 40 minutes of running time at the consumption rates being used. With continued consumption of the emulsified fuel, function of the fuel control became increasingly unsatisfactory and engine speed regulation became increasingly unstable. Except during the first half hour on the emulsified fuel, when some running at 60-percent gas producer speed (flight idle) was accomplished, sustained operation below 70-percent gas producer speed was not possible without danger of flameout. Several attempts to reach the maximum gas producer speed for which the control had been set were unsuccessful. These attempts at high-power operation were made during the later part of the running when some control deterioration had already taken place.

Starts became increasingly difficult with accumulation of operating time on the emulsified fuel. It ultimately became necessary to increase the minimum flow stop of the main metering valve in order to start the engine. Below minimum flow, fuel delivery is unregulated and dependent only on pump capacity, while above this point, fuel flow is scheduled by speed, pressure, temperature, etc. Minimum flow is normally well below ground idle fuel requirement so that the starting fuel is scheduled by gas producer speed. The adjustment made raised the minimum flow to a value approximately that of the flight idle fuel requirement. Thus, the full pump capacity is available during the start and acceleration to flight idle.

After somewhat less than 3 hours of running on emulsion, a very high primary manifold pressure indicated that the flow divider was not functioning properly. It was removed and cleaned, somewhat improving the distribution to primary and secondary manifolds. However, its function was still not completely satisfactory, and the divider was replaced by a solenoid valve which could perform the function of closing off the secondary manifold during low fuel flow operation (during starting).

Engine operation for the final 50 to 60 minutes was extremely unstable. With the power lever at the maximum position, the engine cycled erratically from 50- to 70- and 85- to 88-percent gas producer speed. This behavior resulted from the following combination of influences:

1. The post engine run calibration of the remaining fuel pump element revealed severe deterioration in output flow versus discharge pressure. This, combined with the higher-than-normal fuel system pressures caused by clogging of downstream components, reduced

the pump capacity. Thus, the fuel system was unable to meet the demands of the engine power lever position, and the level of engine rpm dropped off.

2. The fuel control pressure regulating valve, which had been scored by contaminants, caused sluggish and erratic regulation of the metering valve pressure drop. As a result, the engine operation was unstable.

The erratic and sluggish behavior of the control during engine testing did not manifest itself on the Phase I bench testing for the following reasons:

1. Pump flow deterioration had not progressed to any great extent during the limited time consumed in bench calibrations.

2. Bench calibrations were performed with lower pump discharge pressures than were experienced on the engine.

3. The bench calibration does not isolate the steady-state operating points of the engine, but rather defines the operating characteristics of the governors off-steady state. Thus, it takes the engine to close the loop and demand the proper fuel from the control.

After 3:13 hours of operation on emulsified fuel, one element of the two-element fuel pump ceased to function. This occurred as the inlet pressure became slightly negative because of a malfunction of the console pump. Although the changeover to JP-4 fuel was made in time to prevent flameout, it is thought that the momentary loss of inlet pressure may have caused cavitation, resulting in momentary seizure of the element which caused failure at the drive shaft in the shear section. The system was changed back to emulsified fuel and running was continued, in a very unstable manner, for 18 additional minutes. The engine was then shut down to clean the pressure regulating valve. Several attempts to restart were unsuccessful; it was concluded that the one remaining pump element, which had already deteriorated, could not provide sufficient starting fuel. It was then decided to terminate operation on emulsified fuel. Total running time accumulated on the fuel was 3:31 hours. It might be noted that when instability or lack of control developed while operating with emulsified fuel, the situation could not be corrected simply by switching back to JP-4 fuel. Removal and cleaning of the pressure regulating valve and/or flushing the control with water was necessary to gain any improvement in control function.

Performance of the basic engine, apart from the fuel system, is somewhat difficult to assess because of the fuel control instability which prevented the obtaining of steady-state data, and partly because of the difficulty in accurately measuring the flow rate of the emulsified fuel.

Figures 71 through 74 show performance data obtained on JP-4 fuel prior to the operation with emulsified fuel. Included in these figures are such data as it was possible to obtain from operation with emulsified fuel. Except for two low-power data points taken in the first half hour of emulsified fuel operation, the points shown are for unstabilized conditions; i.e., the data were taken after only 30 seconds to 1 minute at the point. Figure 71 shows referred fuel flow versus referred gas producer speed. The two steady-state readings appear to be abnormally high. However, these readings were made with the Cox turbine flow element, and it is felt that the fuel passing through the element had not completely liquified, thereby causing inaccurate flow measurement. The other points were measured with the linear mass flowmeter. These are within 2 percent of the JP-4 fuel calibration. Referred shaft horsepower versus referred gas producer speed (Figure 72) shows power on emulsified fuel to be within 5 percent of that on JP-4 fuel. It must be noted that these data were obtained under conditions not conducive to good accuracy. With the instability caused by the fuel control malfunction, it was difficult to insure that all parameters were read at the same condition. In addition, it is known that data taken when the engine has been on a point for only 30 to 60 seconds, as was the case here, are less valid than those taken after the engine has stabilized for 3 to 5 minutes. Specific fuel consumption (Figure 73) shows approximately 3-percent depreciation using the actual flow rate of the emulsified fuel. When flow rate is corrected for weight of water in the emulsified fuel, depreciation appears negligible. Exhaust gas temperature versus gas producer speed (Figure 74) shows no consistent effect of using emulsified fuel.

Because of the fuel control difficulties, only one transient was attempted with emulsified fuel. This was accomplished immediately after a changeover from JP-4 fuel. Sanborn tracings of this transient, and one on JP-4 fuel performed just before the fuel changeover, are shown in Figures 75 and 76. Although acceleration between 70- and 90-percent gas producer speed is approximately one-half second slower with the emulsified fuel, it appears that this is a problem of how the fuel is scheduled by the control, not one of response of the engine itself. During a jam acceleration, the ratio of fuel flow (W_f) to compressor discharge pressure (P_3) should be a given value, determined by a cam, for any gas producer speed. Observation of the traces, taking secondary manifold pressure as

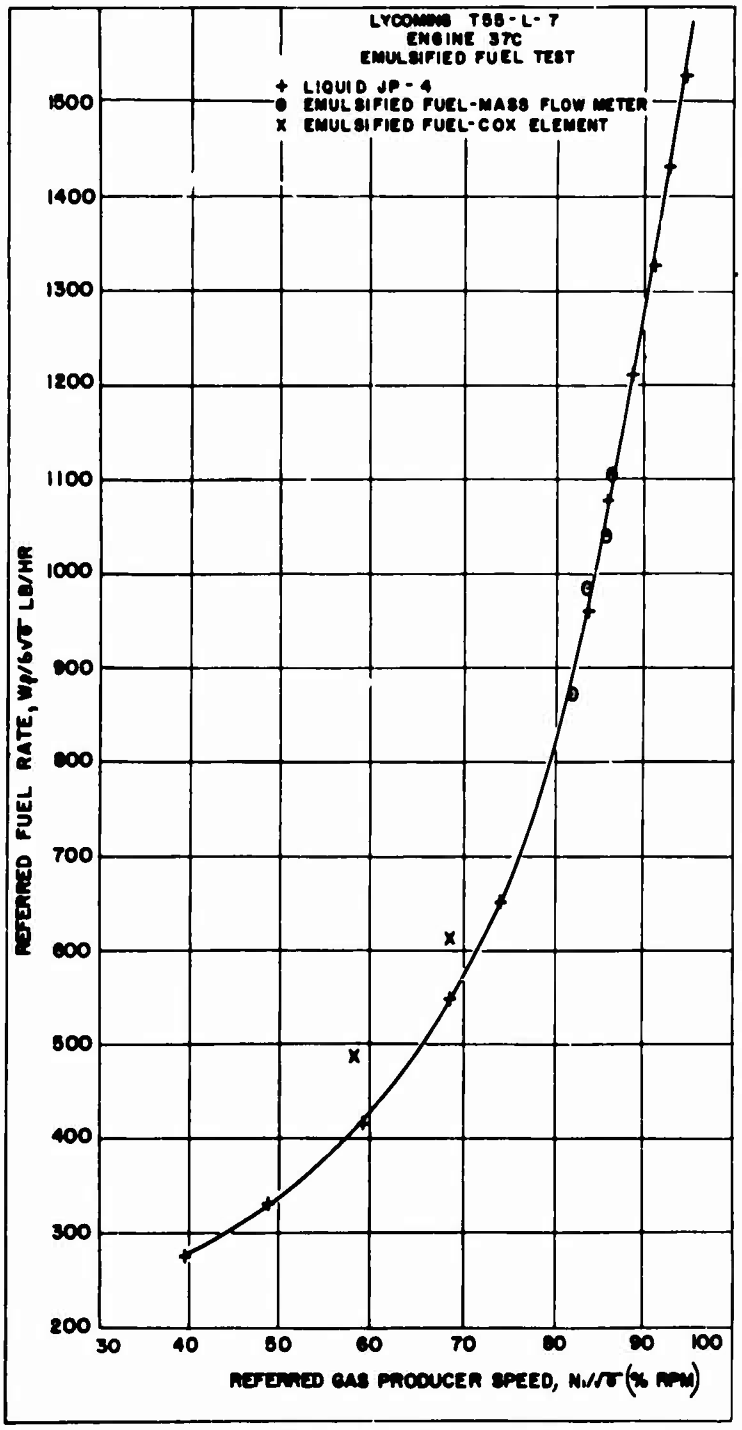


Figure 71. Referred Fuel Flow Versus Referred Gas Producer Speed.

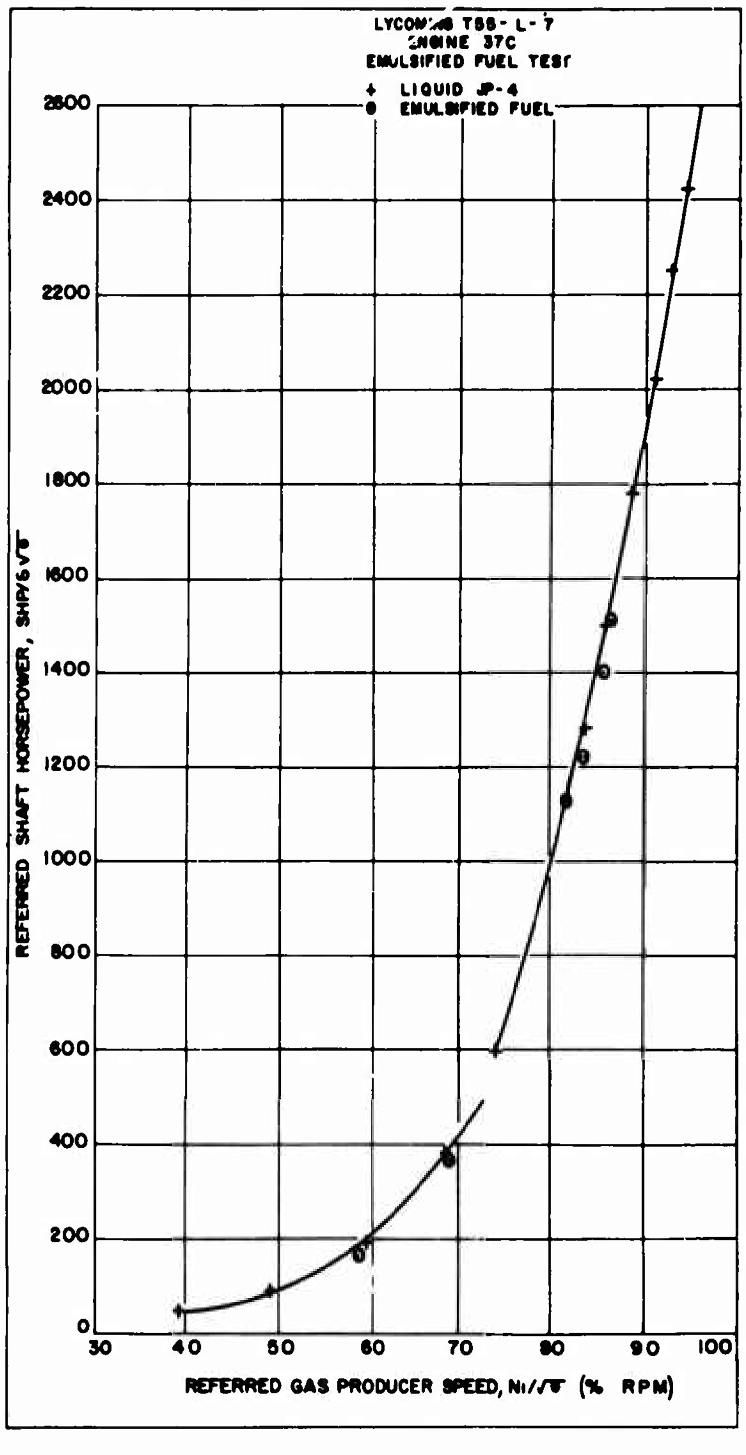


Figure 72. Referred Shaft Horsepower Versus Referred Gas Producer Speed.

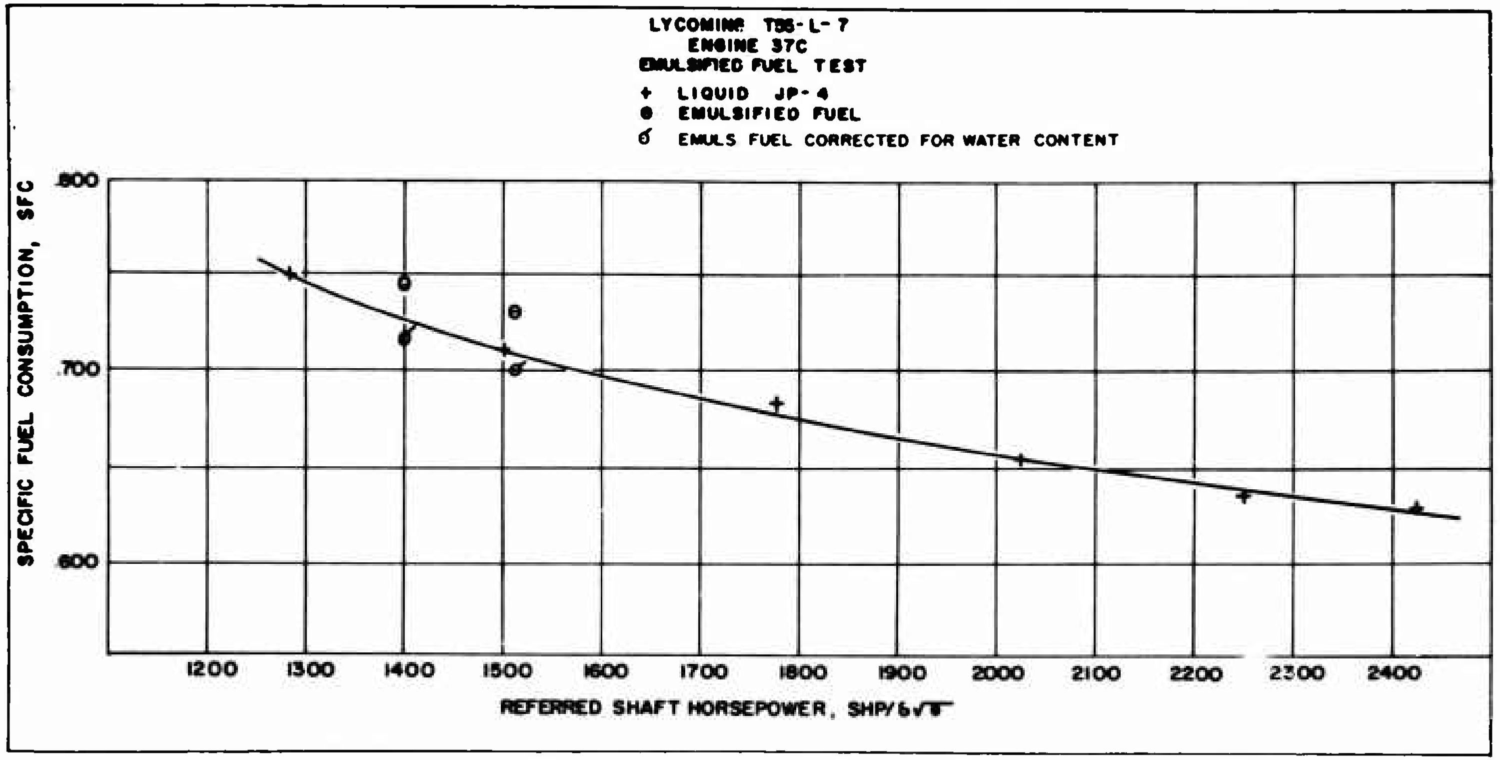


Figure 73. Specific Fuel Consumption Versus Referred Shaft Horsepower.

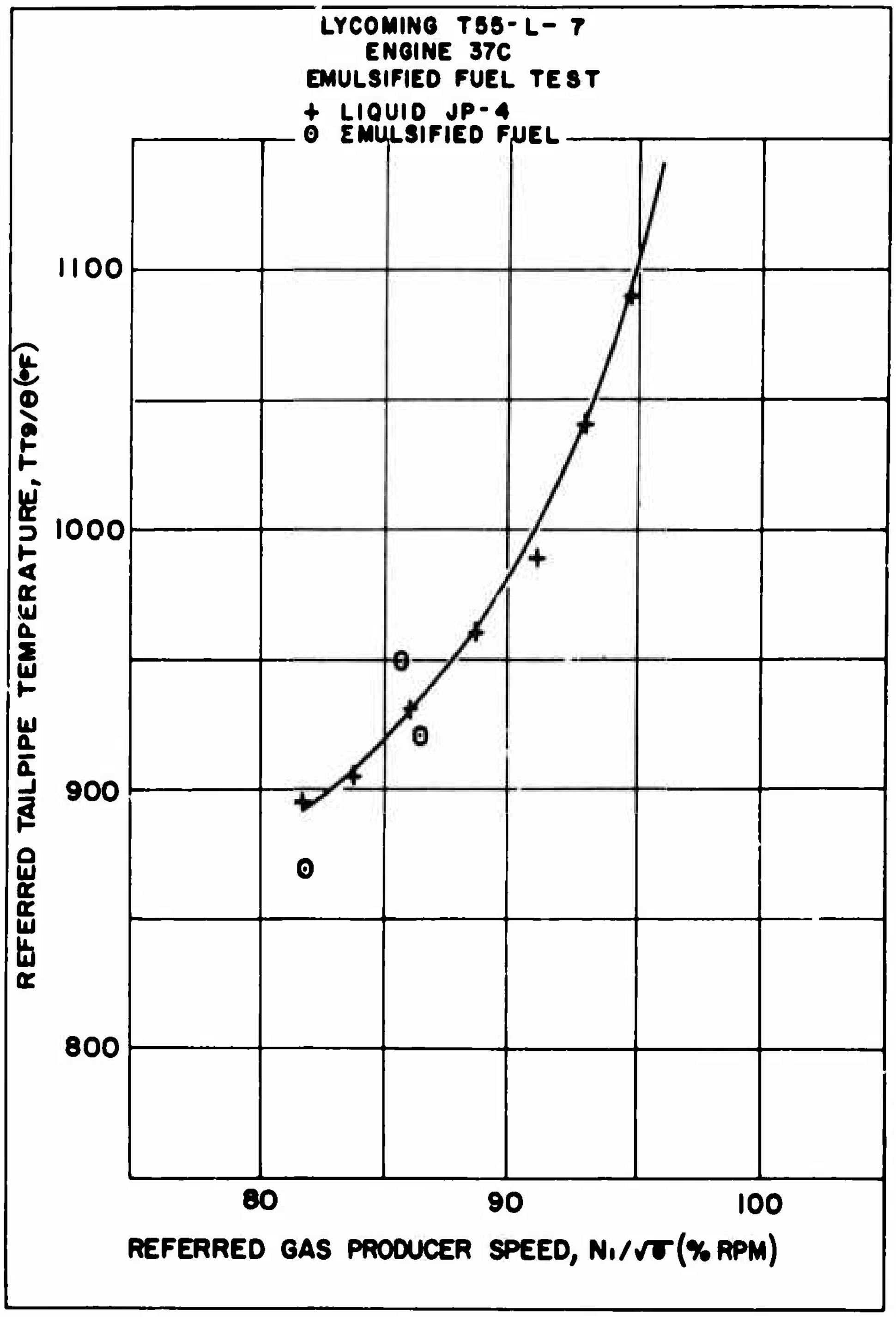
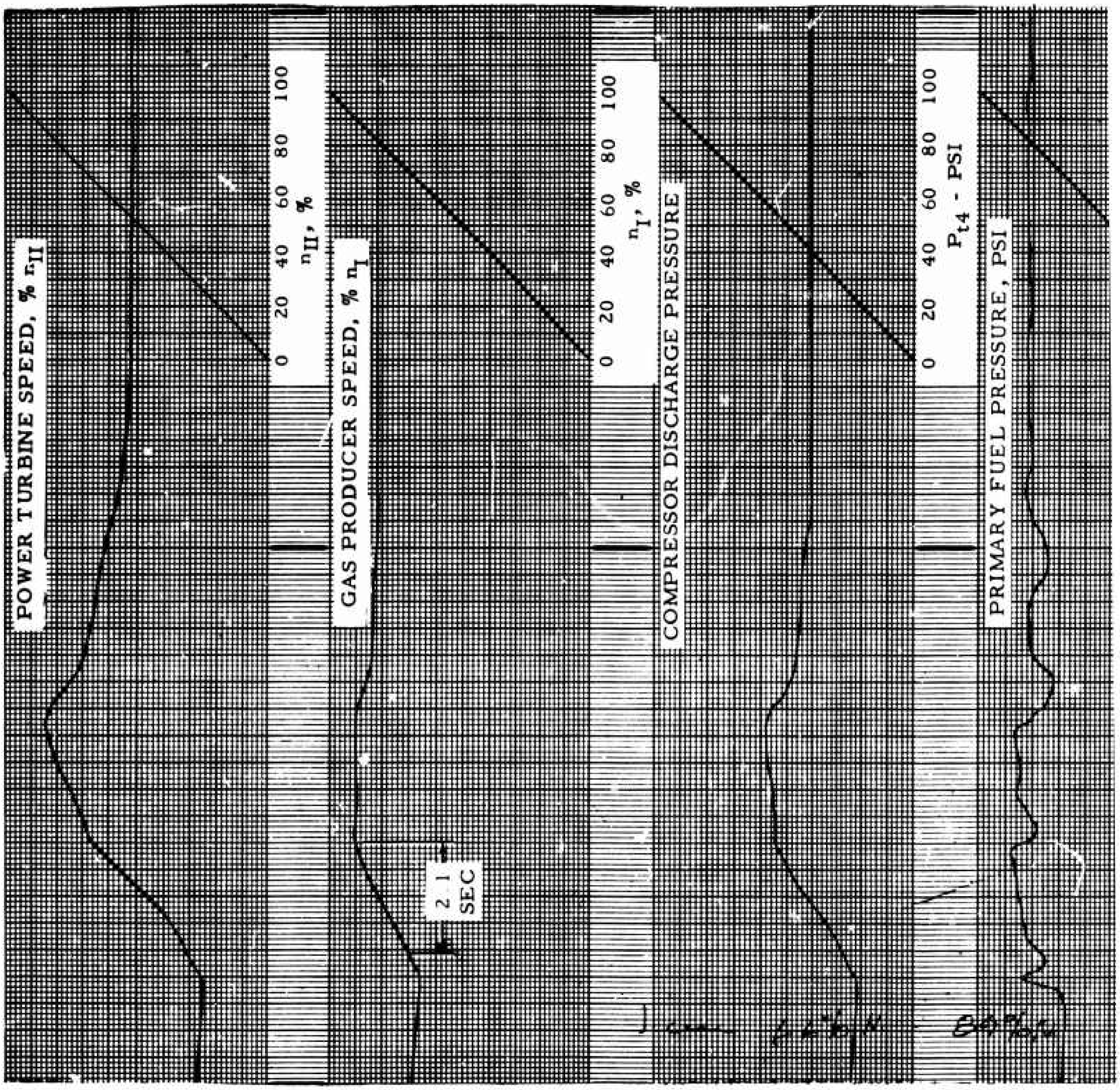
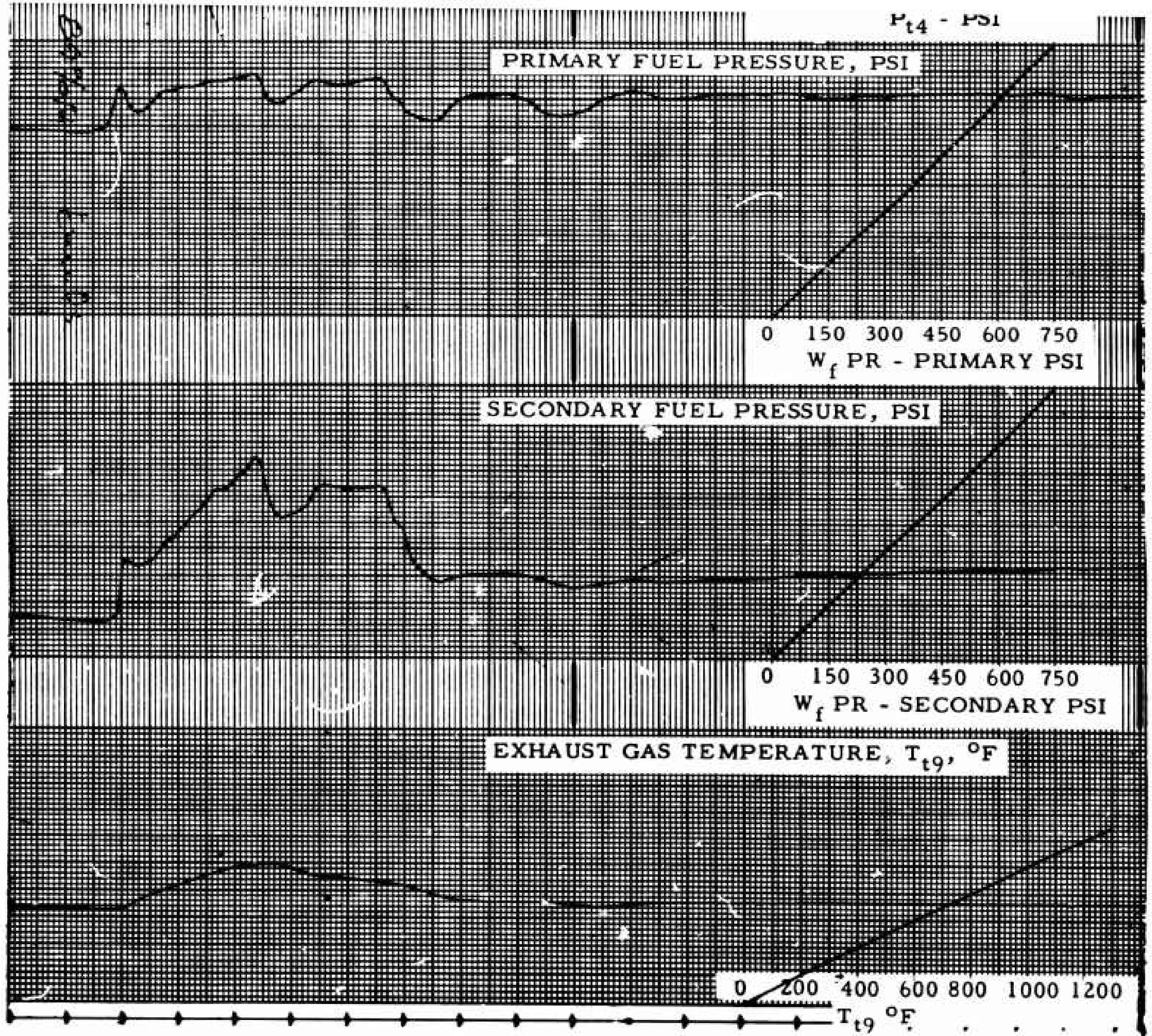


Figure 74. Referred Exhaust Gas Temperature Versus Referred Gas Producer Speed.


POWER TURBINE SPEED, % n_{II}
0 20 40 60 80 100
n_{II}, %
GAS PRODUCER SPEED, % n_I
0 20 40 60 80 100
n_I, %
COMPRESSOR DISCHARGE PRESSURE
0 20 40 60 80 100
P_{t4} - PSI
PRIMARY FUEL PRESSURE, PSI
2.1 SEC

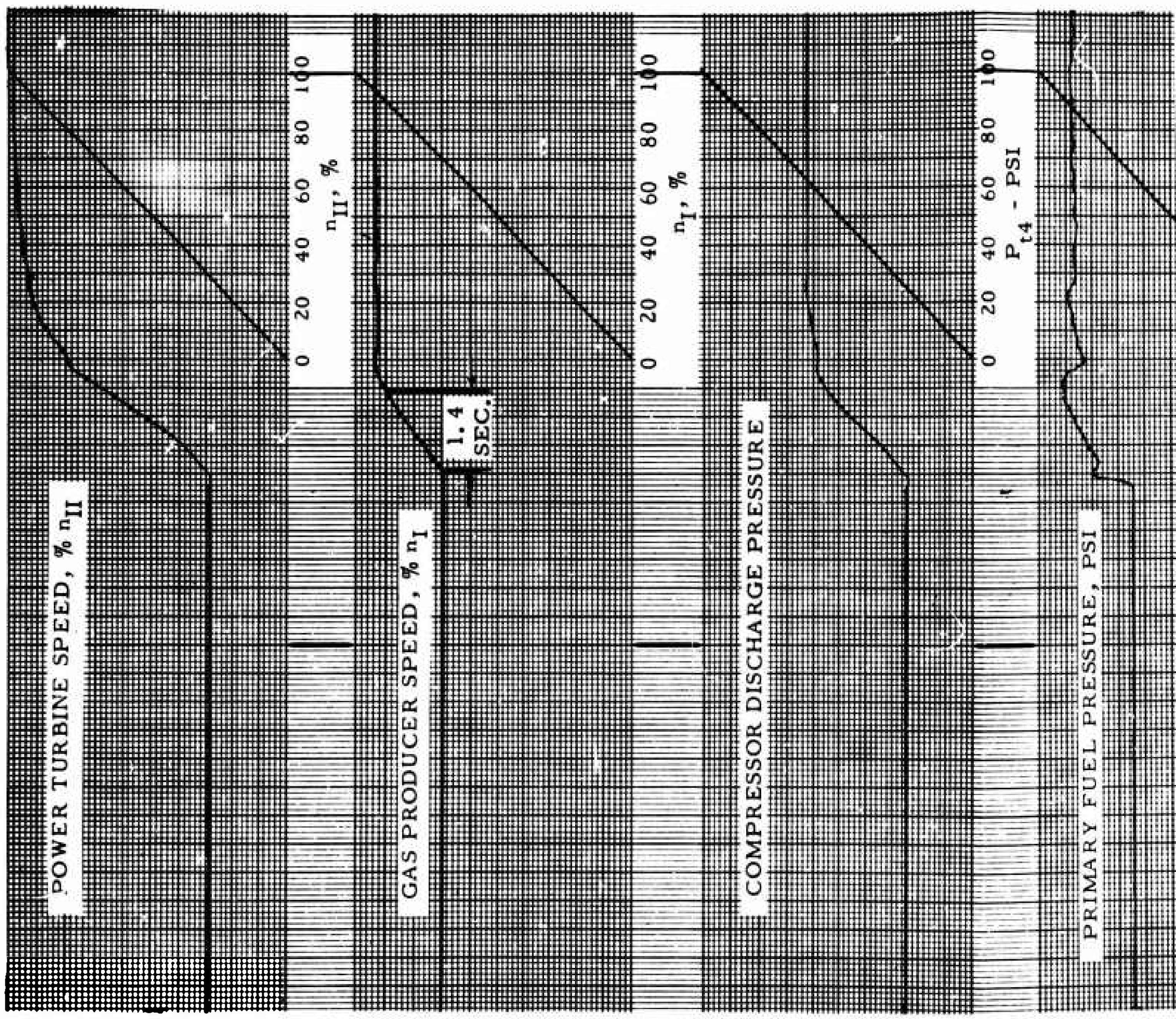
A



B

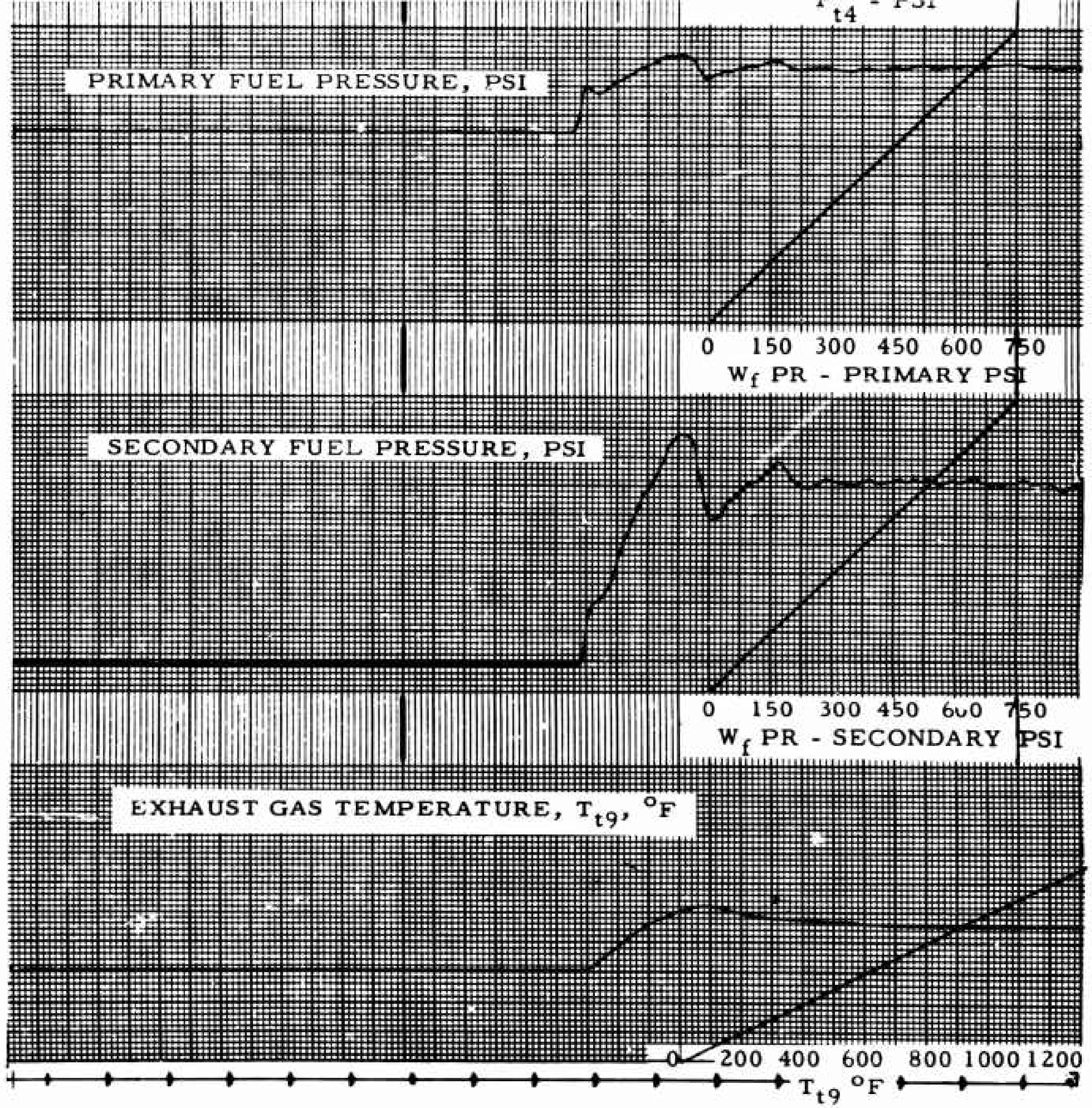
LYCOMING T55-L-7 ENGINE 37C
POWER TRANSIENTS
JAM ACCELERATION FROM 70% TO 90% N_1 SPEED
EMULSIFIED FUEL

Figure 75. Sanborn Recording of Jam Acceleration With Emulsified Fuel.



POWER TURBINE SPEED, % n_{II}
0 20 40 60 80 100
n_{II}, %
GAS PRODUCER SPEED, % n_I
1.4 SEC.
0 20 40 60 80 100
n_I, %
COMPRESSOR DISCHARGE PRESSURE
0 20 40 60 80 100
P_{t4} - PSI
PRIMARY FUEL PRESSURE, PSI

A



LYCOMING T55-L-7 ENGINE 37C
POWER TRANSIENTS
JAM ACCELERATION FROM 70% TO 90% N₁ SPEED
LIQUIFIED JP-4 FUEL

Figure 76. Sanborn Recording of Jam Acceleration With JP-4.

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an indication of fuel flow, will show that the W_f/P_3 ratio is lower with the emulsified fuel, thereby causing a slower acceleration. This leaner ratio presumably results from the effects of emulsified fuel in the passages and servos of the control.

Although the data are somewhat limited to permit any definite conclusions, it would appear that deterioration of engine performance, both steady-state and transient, will not be the major problem in operating with emulsified fuel. It should be noted, however, that operation below flight idle (60-percent gas producer speed) could not be accomplished, and was very uncertain below 70-percent gas producer speed. This condition is attributed to the fuel control difficulties. It is possible, however, that this fuel may not be satisfactory in low-power operation where combustion is known to be less efficient, even if fuel control problems should be resolved. This operating range, and transient operation, should be fully investigated when a satisfactory method of power control is devised. Because of the difficulty on starting even with JP-4 fuel, no attempts were made to start with the system filled with emulsified fuel. This operation must also be investigated when a suitable control is available.

It is apparent from the testing accomplished in this program that the existing fuel system presents the major impediment to satisfactory operation with this emulsified fuel. The engine can operate only a few minutes on the fuel before an instability and lack of control response occur. Continued operation causes deterioration of the pump and corrosion within the control. The pump deterioration apparently results from wear caused by solid contaminants carried in the fuel, and such contaminants may also be a contributory factor in sticking of servos in the computer section. Elimination of those contaminants appears to be a major problem, however. The emulsion clogs all the filters in the system almost immediately, causing the filter bypasses to open. This leaves the fine clearances in fuel control and fuel nozzles unprotected from dirt. Corrosion within the control could undoubtedly be reduced or eliminated by use of a nonaqueous, noncorrosive emulsion. Considerable fuel system development would be required to enable satisfactory use of this particular emulsified fuel.

POSTTEST INSPECTION

The only internal engine components which appear to have suffered from the use of emulsified fuel are the fuel nozzles. These became continually more clogged with corrosion products as the test progressed. Table IV shows the flowbench calibrations for one-half of the manifold before

TABLE IV

FUEL NOZZLE FLOW AT 100 PSI

	Primary (cc/120 sec)		Primary + Secondary (cc/60 sec)	
Nozzle No.	Before Test	After Test	Before Test	After Test
15	127	132	325	215
16	134	150	349	301
17	128	141	345	311
18	130	125	344	265
19	126	124	343	278
20	132	104	352	260
21	125	94	343	271
22	125	85	355	132
23	121	80	350	245
24	125	65	340	185
25	132	44	330	154
26	130	Plugged	352	93
27	130	Plugged	342	141
28	121	35	332	236

and after the emulsified fuel test. It can be seen that flow is, in general, much lower for the same pressure; consequently, any given fuel flow requires a higher pressure. As noted above, this places greater requirements on the fuel pump, which is already adversely affected by the emulsion.

Judging from the other manifold half, which was not flow checked but was disassembled for inspection, the blockage occurred not in the 0.007- to 0.008-inch orifice, but in the protective screens, which have 0.004-inch mesh. These screens have a brownish deposit, which appears to be composed partly of products of corrosion. Since all filters in the system go to bypass with the emulsified fuel, it is felt that dirt being carried in the fuel also contributed significantly to the screen clogging.

Figures 77 through 79 show typical nozzle and manifold conditions at the completion of the test.

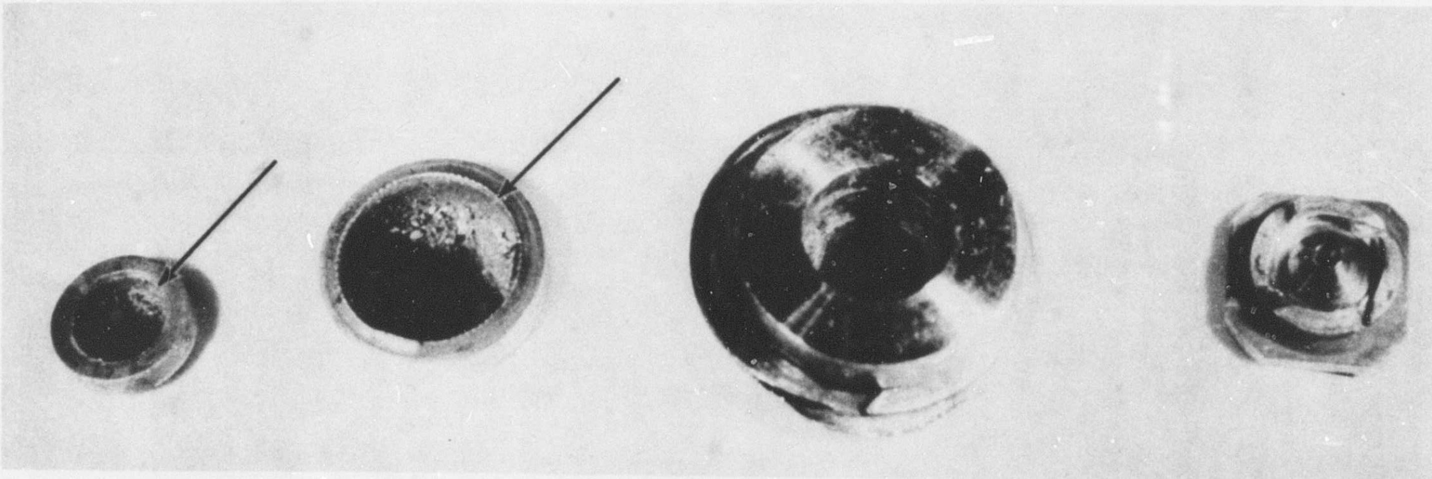

Figure 77. Fuel Nozzle Components After Engine Test. Left to Right: Primary Screen, Secondary Screen, Nozzle Body, Swirl Chamber. Note accumulation of deposits in both screens (arrows). Magnification: 6X

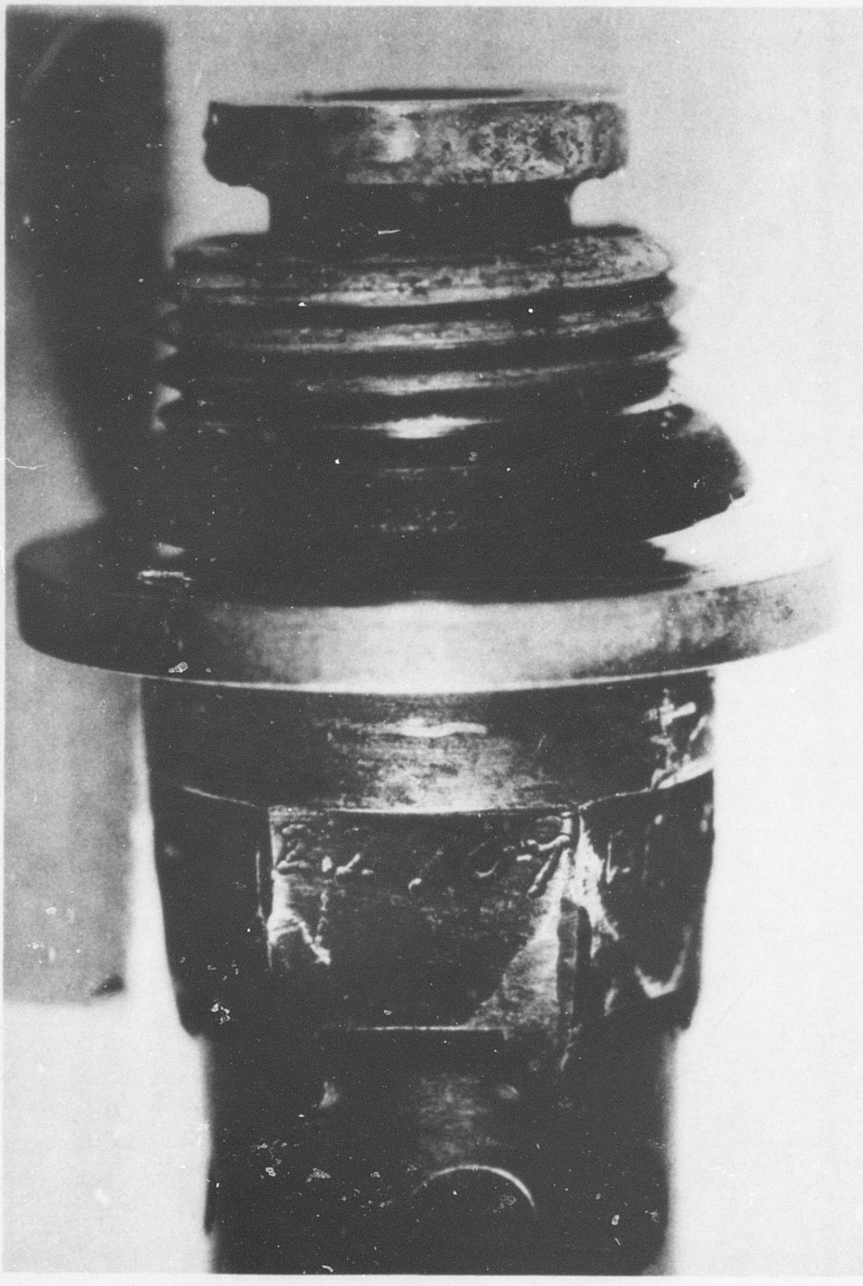

Figure 78. Fuel Nozzle After Engine Test Showing Deposits on Inlet End; Close-Up View. Magnification: 10X

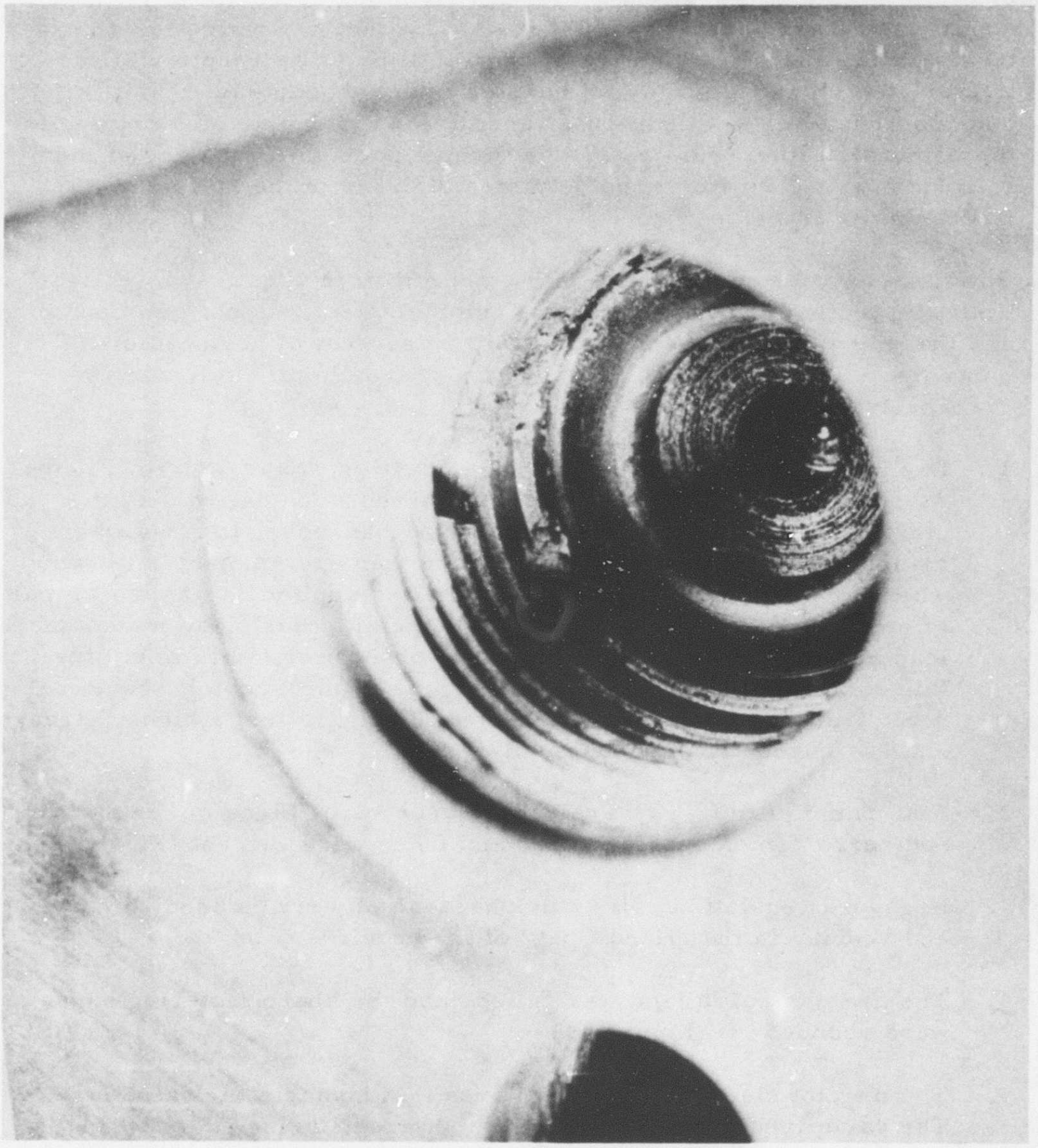

Figure 79. Fuel Manifold After Engine Test Showing Deposits in Nozzle Receptacle; Close-Up View. Magnification: 8X

The hot section of the engine was disassembled for inspection following the test. Except for the fuel nozzles discussed above, there appeared to be no unusual conditions which could be attributed to the use of emulsified fuel. It should be remembered, however, that there was no endurance running, and power level was limited. Operation for an extended time, and/or at high power, might alter these results. In particular, the clogging of the fuel nozzles would undoubtedly result in combustor hot spots which would cause local burning and distortion of the combustor liner and first-stage turbine nozzle. If clogging of the fuel nozzles is eliminated, no detrimental effect of the fuel on parts life would be expected.

The fuel control was returned to the laboratory for posttest investigation. Rig testing confirmed that one pump element was not functioning and that the second was delivering only 60 percent of normal flow. The control was disassembled for inspection, revealing the following discrepancies:

1. One pump element drive shaft shear section was fractured (Figure 80). As noted on page 120, this failure occurred when delivery of the emulsified fuel was interrupted, and a changeover to JP-4 was made. It is hypothesized that the pump ran dry momentarily, and when the pressure of the JP-4 supply was applied, a semisolid mass of emulsified fuel was forced into the pump, causing an instantaneous load application estimated to be 1.5 horsepower. With liquid fuel, this shock loading would probably not have occurred. It should be noted that this shaft is of an obsolete configuration; a higher strength shaft is currently in production.

2. Both pump gear faces were excessively worn. Signs of contaminant and corrosion on bearing bores and faces were evident (Figure 81).

3. Pressure regulating valve stuck because of wear on anodized bore and scoring in the "Hard Coat" of the spool.

4. The n_{II} pilot valve land was galled, and the sharp metering edges were rounded off (Figure 82).

5. The n_I pilot sleeve was worn in area that contacts the valve land. The valve land was galled, and the sharp metering edges were rounded.

6. The pressure ratio servo sleeve was severely oxidized (Figure 83) and deposits of aluminum oxide mixed with emulsion were packed

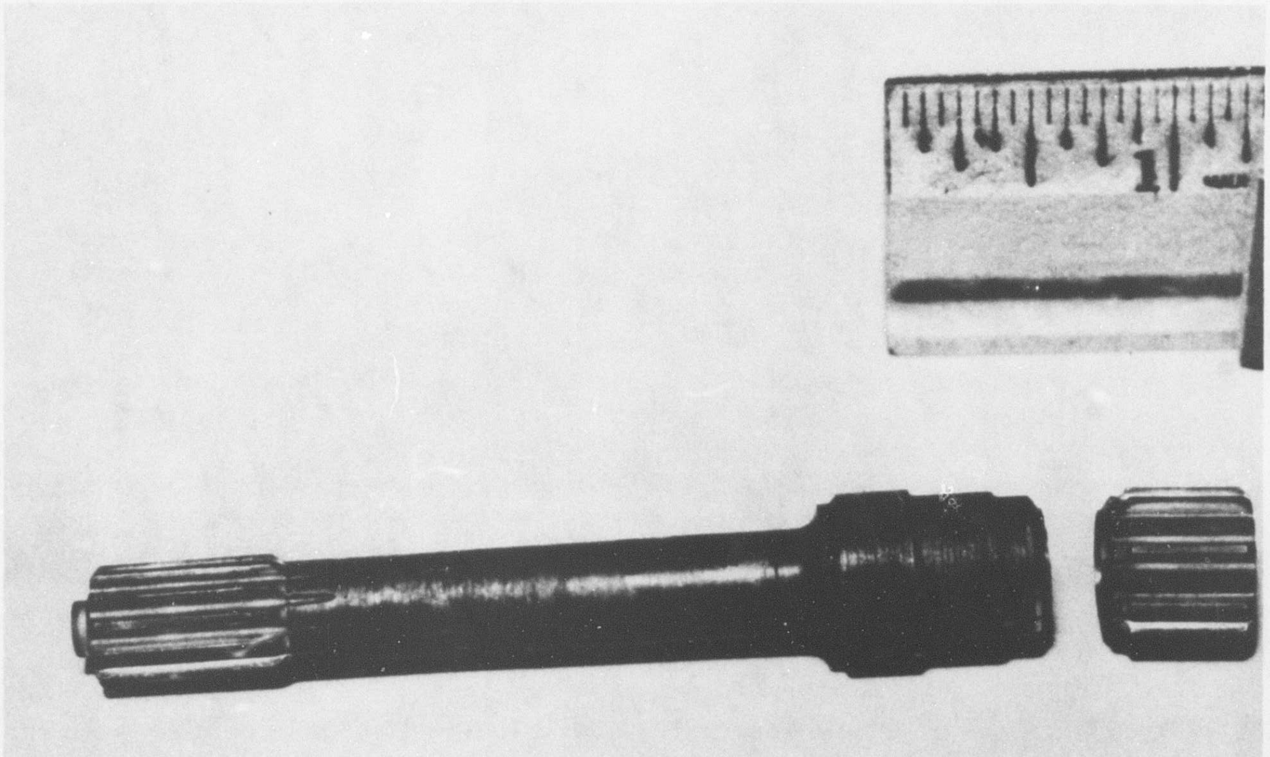

Figure 80. Fuel Pump Drive Shaft Showing Failure at Shear Section.

Figure 81. Fuel Pump Element Showing Worn Faces on Gears and Bearings (Arrows).

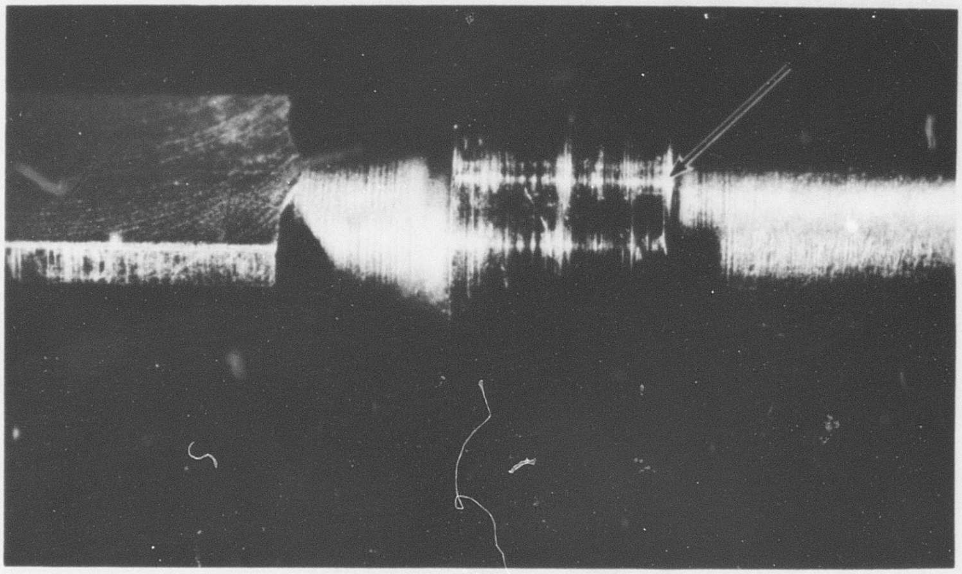

Figure 82. The n_{II} Pilot Valve Showing Scored Land With Rounded Metering Edge (Arrow).

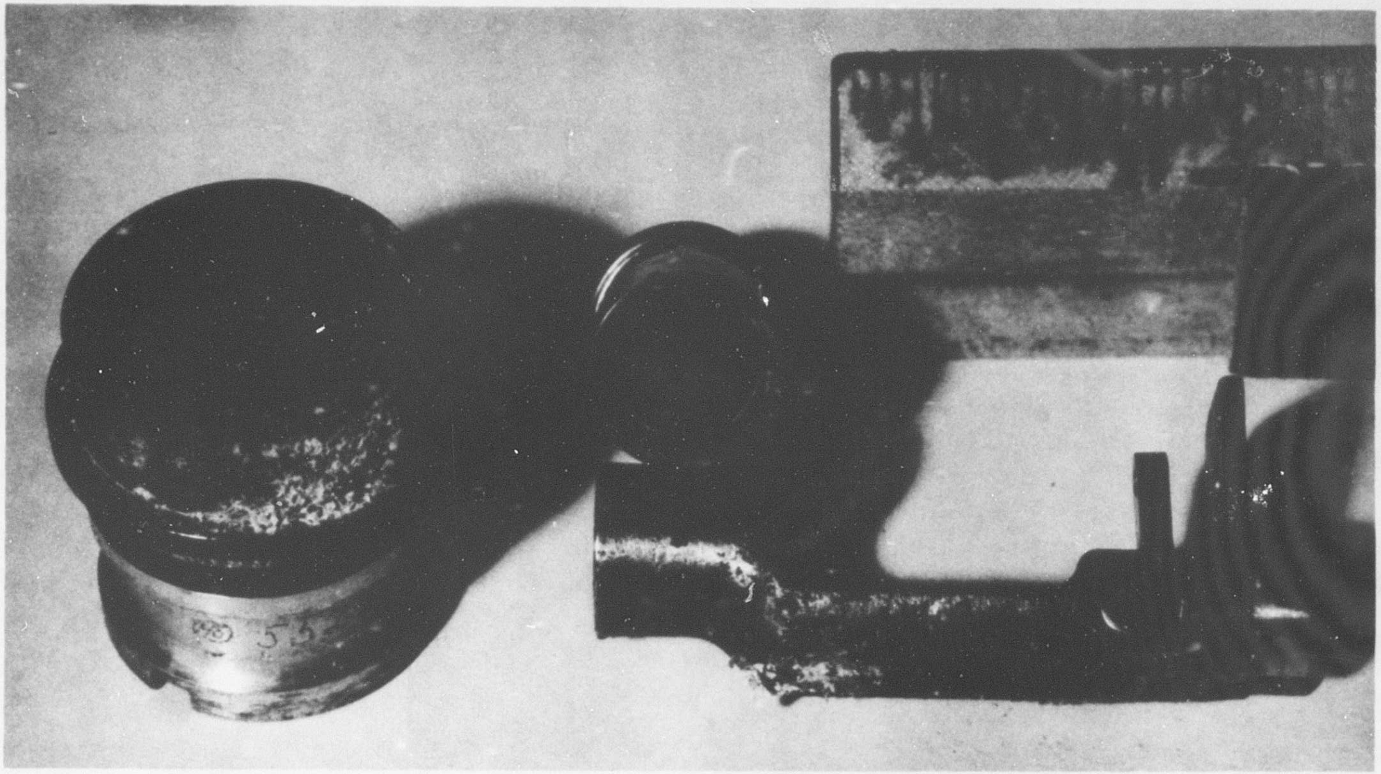

Figure 83. Corrosion and Deposits on Aluminum Pressure Ratio Servo Sleeve (Left) and Steel Torquemeter Linkage (Right).

behind the sleeve.

7. The n_I flyweight head bearings were packed with deposits of oxide and emulsion.

8. The P_3 servo flapper was partially clogged with oxide; the anodized bore of the P_3 servo was worn away over 80 percent of the P_3 servo stroke. The housing and linkage were oxidized to an extent that would cause excessive hysteresis (Figure 84). The P_3 bellows convolutions were plugged with a mixture of emulsion and oxide (Figure 85).

9. The aluminum housings were all irregularly pitted with corrosion.

10. The steel linkages displayed varying degrees of rusting (Figure 86).

The rust generated by the emulsion within the control adhered to the computer links and did not reach the point of scaling off. Therefore, galling and wear of the hardened surface parts are most likely caused by the contaminant carried into the control from the fuel supply system.

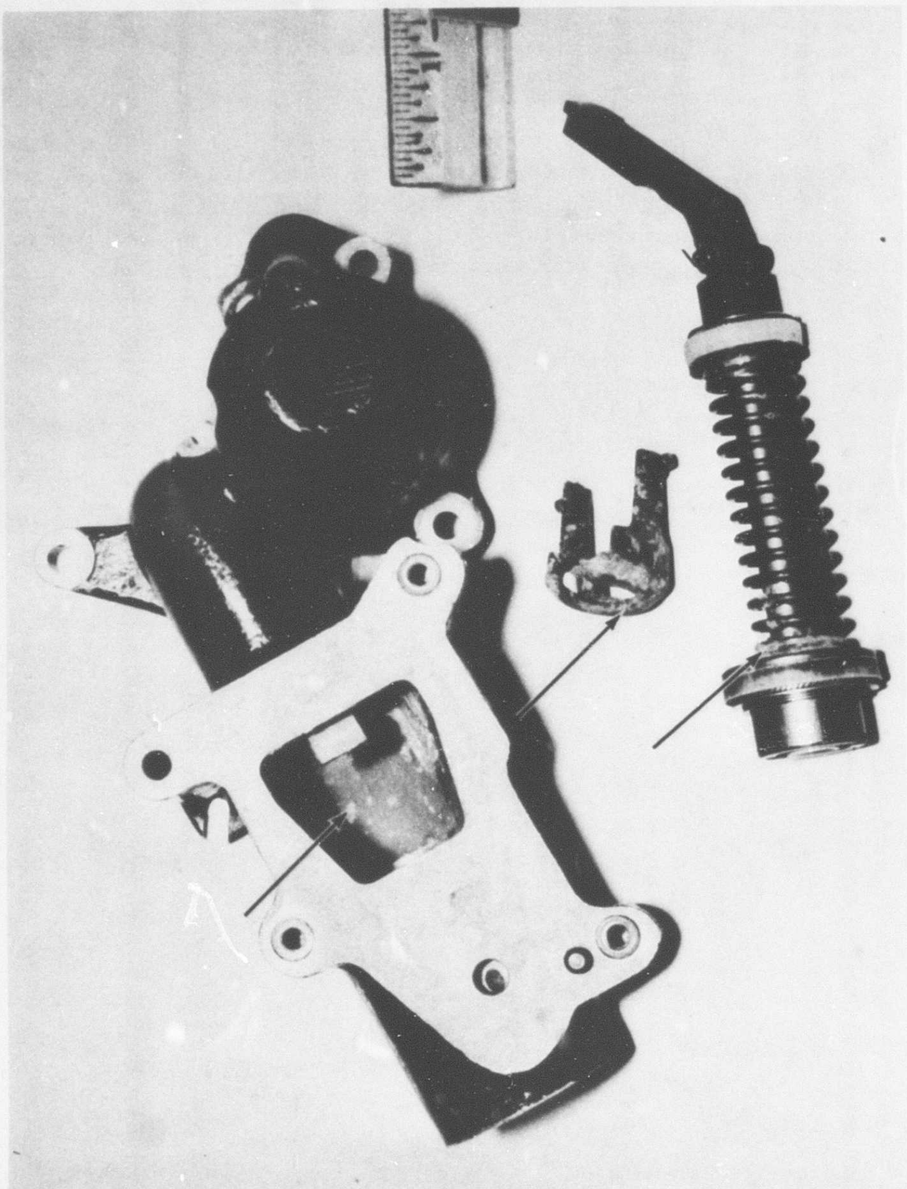

Figure 84. P_3 Servo and Housing and Linkage Showing Oxidation and Deposits (Arrows).

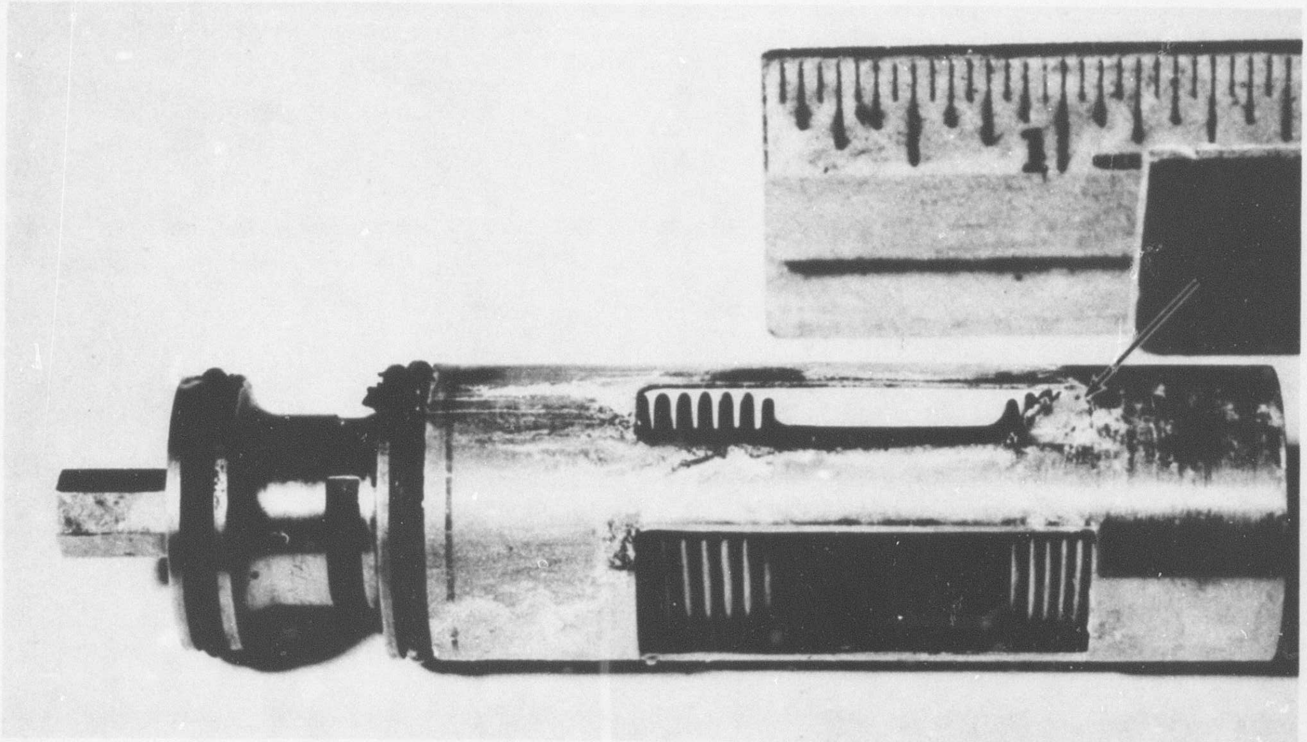

Figure 85. Bellows Assembly Partially Plugged With Oxide and Emulsion (Arrow).

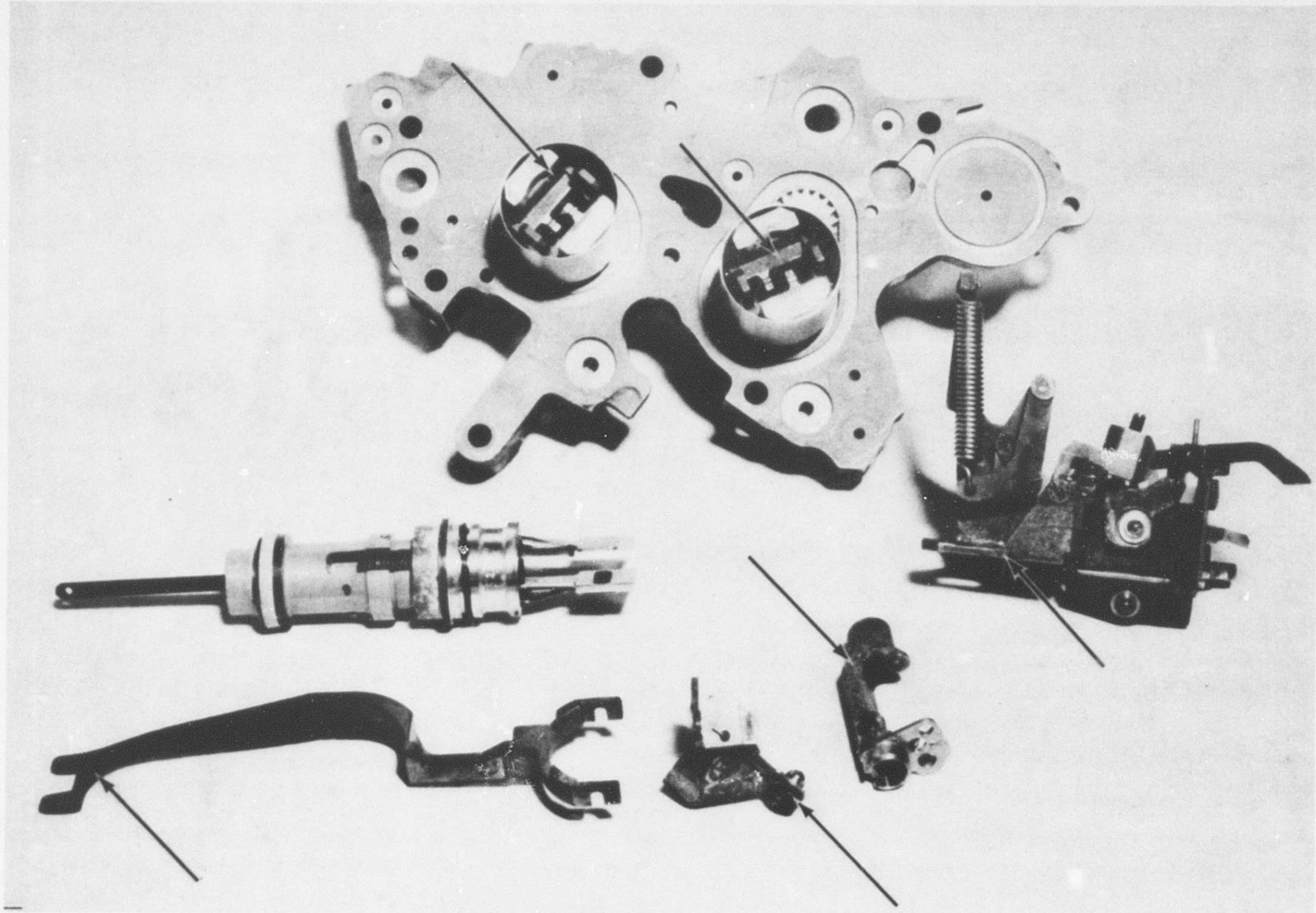

Figure 86. Flyweight Housing (Top), W_f/P_3 Servo (Left Center), and Various Linkages. Arrows indicate rusted areas.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the bench tests and engine operation conducted on JD-1 emulsified fuel, the following conclusions are drawn:

1. Although the bench test of the fuel system indicated that the JFC-31 fuel control in use on the T55 engine was capable of properly scheduling and delivering fuel flow, actual engine operation has shown that the control in its present configuration is not suitable for use with the Western Company-formulated emulsified fuel for several reasons.

    a. The emulsion causes corrosion of the steel linkages and aluminum housing of the control, with resultant contaminants.

    b. Contaminants now entrained in the emulsion cause excessive wear throughout pump and control.

2. Both bench test and engine test showed that the emulsion clogs filters in the system almost immediately, causing the bypasses to open and leave critical areas of fuel control and fuel atomizing nozzles unprotected from contaminants carried in the fuel.

3. It does not appear that deterioration in steady-state and transient performance of the engine, apart from the fuel system, will be a serious limitation to running on emulsified fuel. Data supporting this conclusion are limited, however.

4. Except for clogging of fuel nozzles, caused by corrosion and contamination, and the consequential results of poor combustor temperature distribution, the effect of emulsified fuel on parts life should not be significant. Again, it must be cautioned that this conclusion is based on very limited running time.

To improve the ability of the T55 engine to use emulsified fuel, the following recommendations are made:

1. The possibility of modifying the JFC-31 control to enable it to meter and deliver emulsified fuel satisfactorily should be investigated. Alternate types of fuel controls such as electronic and pneumatic should also be studied.

2. Means of effectively filtering the emulsified fuels should be investigated.

3. When a satisfactory fuel control, or interim fuel metering system, is available, considerably more engine testing on a noncorrosive emulsified fuel should be conducted. In addition to the usual performance calibration, this testing should include investigation of starts, transients, low-power operation, and endurance operation.

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PART 5. CONTINENTAL, T-72

by
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Continental Aviation and Engineering Corp.
Detroit, Michigan
Contract DA 44-177-AMC-369(T)

INTRODUCTION

In limited type warfare, it has been demonstrated that the use of an Army aircraft at low altitudes and airspeeds renders its fuel system highly vulnerable to small-arms ground fire. This program is designed to determine the feasibility of burning gelled or emulsified fuel in aircraft gas turbine engines. The advantages of this concept would be threefold: greatly reduced vulnerability of the fuel system to ground fire, postcrash fire hazard reduction, and a greatly reduced ground fuel storage problem. A visual appreciation of the safety features of the fuel and the basic problems related to engine operation are demonstrated in Figures 87 and 88. A pie-shaped section of 2-percent alkylamide gelled JP-4 taken from the top of the engine fuel test sample together with a worm-like section of the same material taken from the engine fuel line after testing is illustrated in Figure 87. A 97-percent emulsion (0.5-percent emulsifying agent and 2.5-percent water) of JP-4 is shown in Figure 88. The two fuels represent two distinct approaches to achieve the same safety goal. The two approaches, however, as might be expected, present some widely different problems as well as similar problems to be solved for successful engine operation.

The end phase of any fuel system is the actual combustion of the fuel within an engine to produce the necessary propulsive power. To achieve this result with a minimum of effort, the program objective of demonstrating the feasibility of burning gelled and emulsified fuel was split into two progressive phases: a laboratory test phase and an engine test phase. The object of the laboratory investigation was to become familiar with the general flow characteristics of the fuels and to determine the effectiveness of the complete engine fuel system using gelled and emulsified fuels. The engine test phase was to demonstrate the feasibility of direct burning gelled and emulsified fuels in an engine.

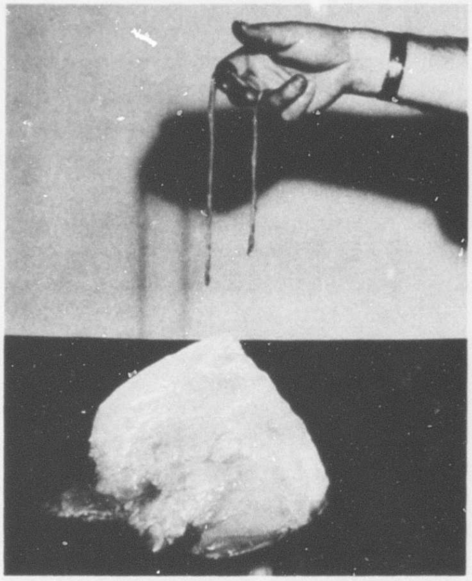


Figure 87. 2-Percent Alkylamide Gelled JP-4.

Figure 88. 97-Percent Emulsion of JP-4.

ENGINE AND FUEL CONTROL DESCRIPTION

The engine used for the feasibility study consisted of the gas generator section of a T72-T-2 (Continental Model 217-5) turboshaft engine. Exterior views of the engine complete with instrumentation are shown in Figures 89 and 90. The left-side view of the engine, Figure 89, shows the dual-element gear type fuel pump, jet nozzle, total pressure probe, and exhaust gas total temperature survey harness. The right-side view, Figure 90, illustrates the fuel control, surge control valve, and related linkage. Also shown is the inlet bell used to measure airflow with its related static pressure and total temperature taps.

A cross-sectional view of the engine is shown in Figure 91. The gas generator section consists of an air inlet housing (1), accessory drive housing (2), a transonic axial compressor rotor (3), a centrifugal compressor rotor (4), an annular combustor section (5 and 6), a rotating fuel distributor (7), and two integrally bladed axial turbines (8 and 9). The aforementioned components are contained within a sheet metal structure which consists of the radial compressor housing (10) and combustor housing (11). The steel structure also houses the one-piece brazed axial diffuser (12), radial diffuser (13), and compressor cover assembly (14). Other stationary aerodynamic components contained within the steel structure are the first- and second-stage turbine inlet nozzles (15 and 16) which incorporate hollow air-cooled vanes to ensure long life at high operating temperatures.

The combustion chamber consists of three sections: an inner shell (6), an outer shell (5), and a primary air admission swirl plate (17) attached to the outer shell by a series of spring clips. Fuel is admitted through a fixed stainless steel manifold (18) which surrounds the main shaft by a steel line (19) that passes through the side (shown out of position on the engine schematic) of the radial compressor housing. This manifold projects under the rotating fuel slinger (7), which is part of the gas generator shaft assembly, and delivers fuel radially out through orifices into the slinger. Energy is then added in the fuel slinger and the fuel is delivered to the combustor through nine holes in the outer diameter of the fuel slinger. Primary air for combustion is supplied through the swirl plate (17). Air which passes through the hollow first-stage turbine inlet nozzle vanes and cools the turbine shaft is also delivered to the primary combustion zone through the front face of the inner combustor. Secondary air is supplied through holes in the outer shell as well as tubes that extend well into the combustor zone.

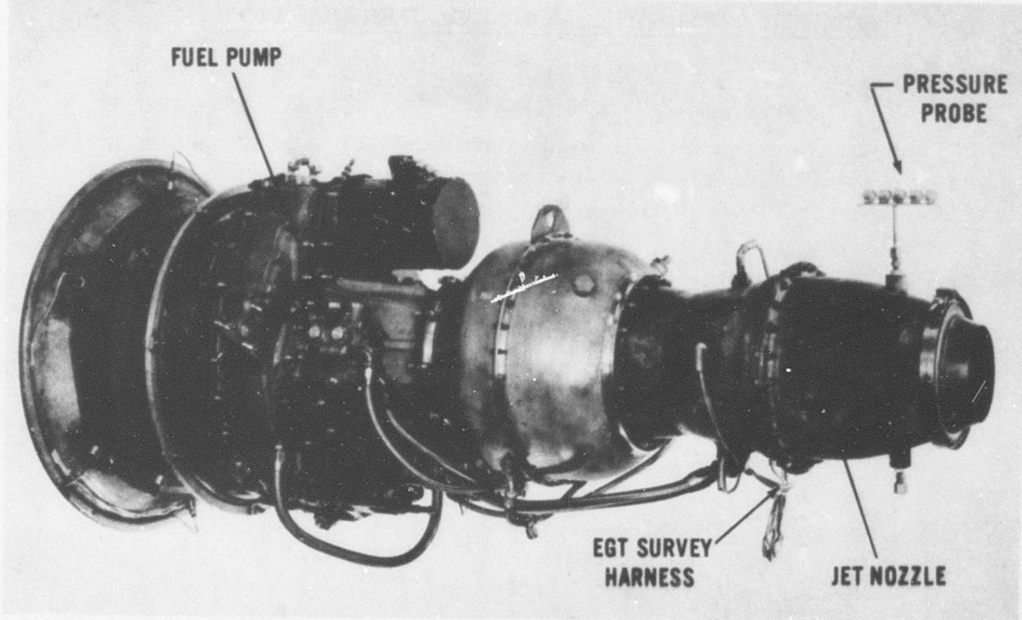


Figure 89. Left-Side View of T72-T-2.

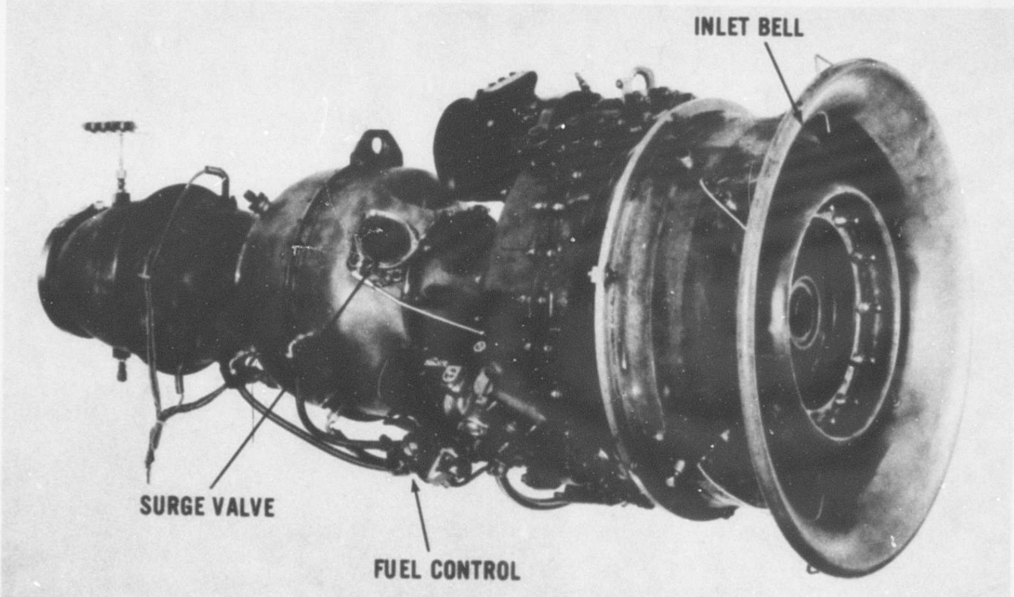


Figure 90. Right-Side View of T72-T-2.

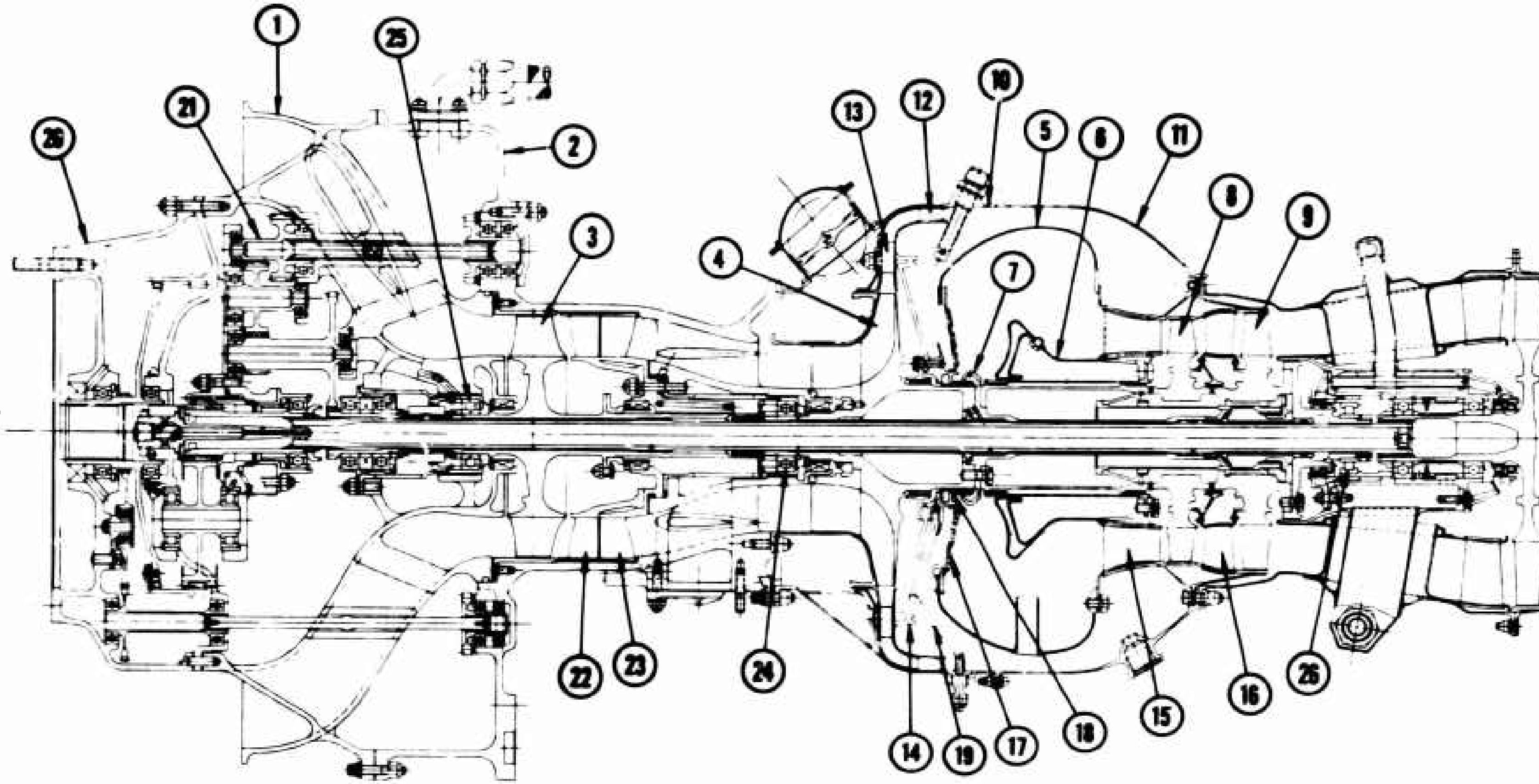


Figure 91. T72-T-2 Cross-Sectional View.

The air inlet housing (1), together with the accessory drive housing (2), forms the annular air inlet passageway which directs the air to the axial compressor section. The air inlet housing also supports the reduction gear assembly (20) and encloses the gas generator accessory drive idler gears (21). The accessory drive housing supports the accessory drive gear train in addition to retaining the two-stage, axial compressor stators (22 and 23). The gas generator shaft assembly is supported by three antifriction bearings: one, a ball bearing at the compressor end, absorbs the thrust loads (24); the second, a roller bearing at the turbine end (26); and the third, the axial compressor rotor bearing (25). All three bearings are mounted in hydrodynamically damped spring supported mounts.

The main control consists of a fuel metering system, a starting fuel system, a compressor bleed valve control, and a reset gas generator governor. The computer section positions the metering valve so that the correct fuel flow is sent to the engine at all times. Metering valve position is determined by compressor discharge pressure, gas generator speed, inlet temperature, and power lever positions. Fuel flow during acceleration is basically a function of compressor discharge pressure as sensed by the control. Variation of the basic schedule with speed, and allowance for change in the compressor inlet temperature, is accomplished by the action of a variable bleed-down air orifice actuated by a three-dimensional cam. The gas generator speed and compressor inlet temperature position the cam, and the follower positions the variable orifice. Thus, complex acceleration schedules are possible.

Increased compressor surge margin at part speed is provided for by a variable air bleed valve positioned by the control as a function of gas generator speed and inlet air temperature. Through a suitable linkage between control and bleed valve, the valve is positioned nearly wide open during starts and at speeds up to ground idle. At higher speeds, it closes gradually until it is fully closed at approximately 90-percent speed. The bleed valve system is operated by the control servo system through an extension of the three-dimensional camshaft.

The following description of the operation of the control can be followed by referring to the fuel control schematic, Figure 92.

Acceleration Schedule

The fuel from the engine pump is scheduled by the main

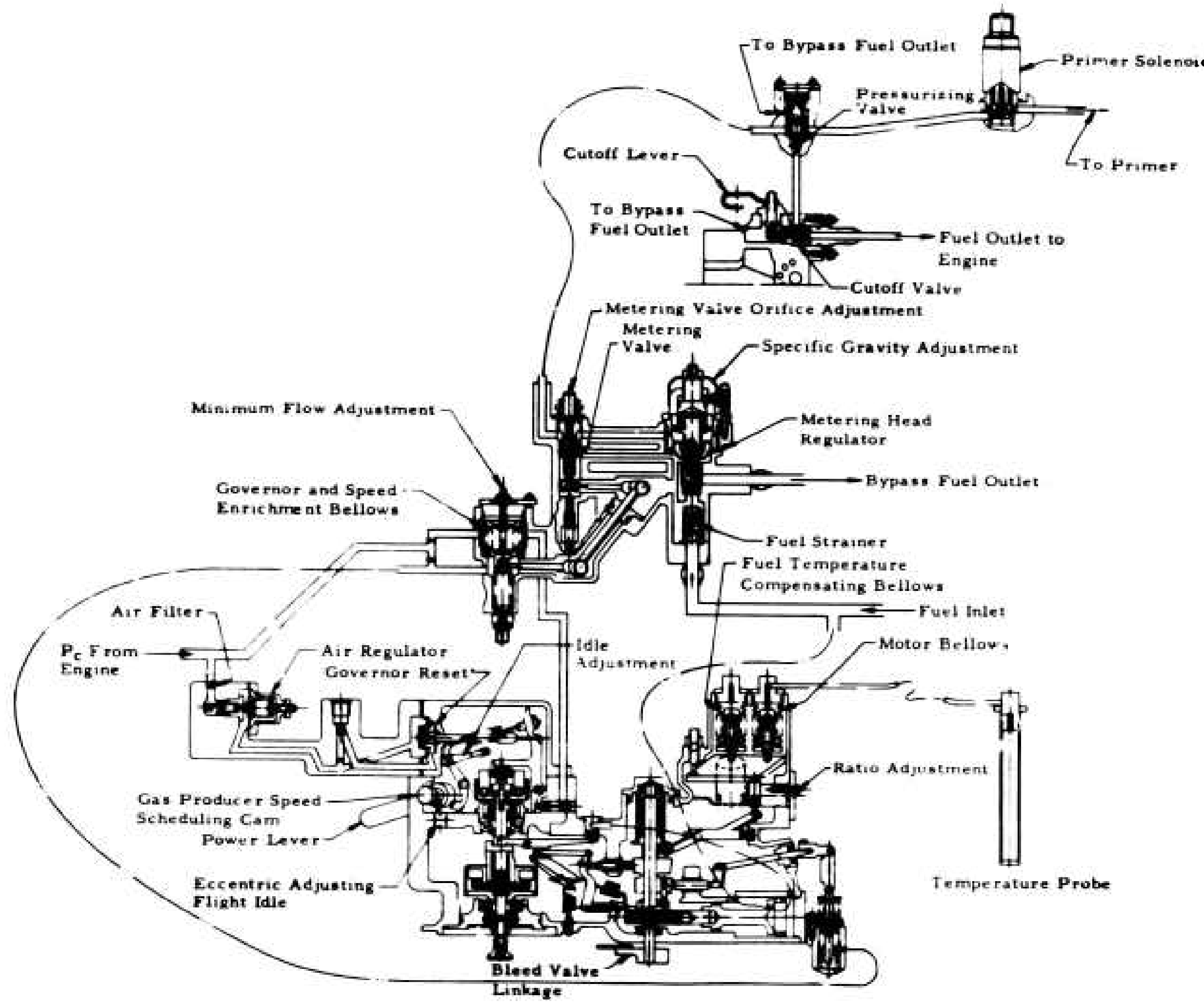


Figure 92. Schematic of Fuel Control.

metering valve and bypass valve. The bypass valve maintains a constant pressure drop across the metering valve and bypasses excess fuel back to the main pump inlet.

Metered fuel flow is therefore proportional to metering area. The metering valve is designed to produce a linear increase in area with travel in the open direction. Valve travel (fuel flow) is computed by a pneumatic computer powered by compressor discharge pressure, P_c. This P_c pressure is supplied through bleeds to P_x and P_y pressure chambers in the control. The P_x pressure is sensed by an evacuated bellows which exerts a force on the metering valve proportional to P_c pressure. A larger area bellows sensing the pressure difference between the P_x and P_y chambers also exerts a force on the metering valve proportional to $(P_x - P_y)$. These combined forces operate against the metering valve system spring rate to position the metering valve. Complex W_f/P_c schedules are met by varying P_x pressure through the action of a bleed down circuit actuated by a T_{t2} biased N_g rotated three-dimensional cam to give the required force output and valve position. It should be noted that the N_g governor valve is closed during the acceleration and that P_y thus equals P_c.

Gas Generator Governor

The gas generator speed is controlled by the gas generator governor. The maximum speed request is established by positioning the power lever which is connected to the speed scheduling cam.

A set of flyweights, opposed by the governor spring load established by the speed scheduling cam, operates through a lever system to schedule the opening of the governor orifice. With the opening of this orifice, a governor pressure drop $(P_y - P_x)$ is developed across the large governor bellows and results in metering valve movement toward the closed position, reducing metered fuel. The governor action is proportional in nature, and the droop rate can be adjusted by changing the governor spring rate or governor bleed sizing.

Acceleration Actuator

In order to achieve the complete W_f/P_c schedules, a three-dimensional cam for scheduling the feedback of a "nut-cracker" speed servo with a flyweight force input is provided. The cam is rotated by the speed servo and translated by T_{t2} temperature inputs to schedule the P_x bleed valve. The "nutcracker" servo uses regulated fuel pressure for power and is a precise method of providing speed outputs as complex functions through use of a feedback cam to improve low-speed gain of the system by permitting linear travel with speed.

Deceleration Schedule

The system provides a fixed minimum level fuel flow for deceleration by stopping the metering valve. An adjustable modified deceleration schedule in direct proportion to the acceleration W_f/P_c ratio is provided by limiting the N_g governor valve travel.

Mechanical Features

A pressurizing valve is provided in the metered fuel circuit to provide proper pressure to the engine primers and to provide minimum pressure for operation of fuel servos in the control during starting. The cutoff valve is a manually operated bypass type in coordination with the throttle lever to meet cutoff schedules. A primer port is provided to supply a 60 $\pm$ 10 psi pressure source to engine supplied nozzles. This flow is controlled by a control-mounted 24-VDC solenoid valve. A self-relieving 61-micron filter is provided in the metering section to protect against line dirt. Further, a separate 44-micron wash type filter is provided in the fuel servo regulator circuit for the same purpose.

INSTRUMENTATION AND DATA ACQUISITION

The static and dynamic instrumentation followed the general practice used by Continental for gas turbine development and evaluation. The following is a list of the instrumentation used during the engine tests.

Compressor Inlet

Inlet flow nozzle for 217-5 engine serial No. PV-1.

Four static pressure taps for inlet pressure difference.

Five I/C total temperature thermocouple probes.

Compressor Discharge

Static pressure tap for 0- to 120-inch H_q Heise gage.

Statham Laboratories Model PG 10TC-75-350 pressure transducer for oscillograph readout.

Fuel Flow

Cox Model LF6-3 turbine flowmeter.

Waugh Engineering Company Model FR-221 frequency convector for oscillograph.

Rotometers - Fisher and Porter calibrated 3-1-66:

(a) Low Scale, 25-125 pounds per hour.
Serial No. W1-1605/2

(b) High Scale, 110-600 pounds per hour.
Serial No. W1-1605/3

Toledo Scale: range 0-1000 pounds.

Standard Timer: 1/1000 minute.

Engine Speed

General Electric tachometer generator.

"Standard" tachometer, 0-80,000-rpm range in 100-rpm increments, calibrated 2-28-66.

Standard small tachometer (geared), 0-60,000-rpm range in 2-rpm increments, calibrated 2-28-66.

Hewlett Packard Frequency Meter Model 500 for oscillograph operation.

Exhaust Gas

Five-position survey harness with four C/A thermocouples per position - 20 couples, total.

Total pressure probe with five pickups, Figure 93.

Exhaust nozzle - 4.860 inches in diameter.

Transient Readout

Consolidated Electronics Corporation recording oscillograph Model 5-124, including Continental fabricated balance box.

Temperature Readout

Two Honeywell-Brown electronic self-balancing potentiometers, one I/C and one C/A, calibrated 4-29-66.

Vibration

International Research and Development Corporation Model 557A.

The Cox turbine flowmeter together with a Cox digital readout system was used for flow measurement during the laboratory test phase. Difficulty was experienced with the repeatability of the readings and thus a simple time-volume method was used as a check. It was found that the turbine element was contamination sensitive. If the turbine element was free and clean, its accuracy was acceptable; however, as dirt and contamination accumulated in the element, its performance became erratic.

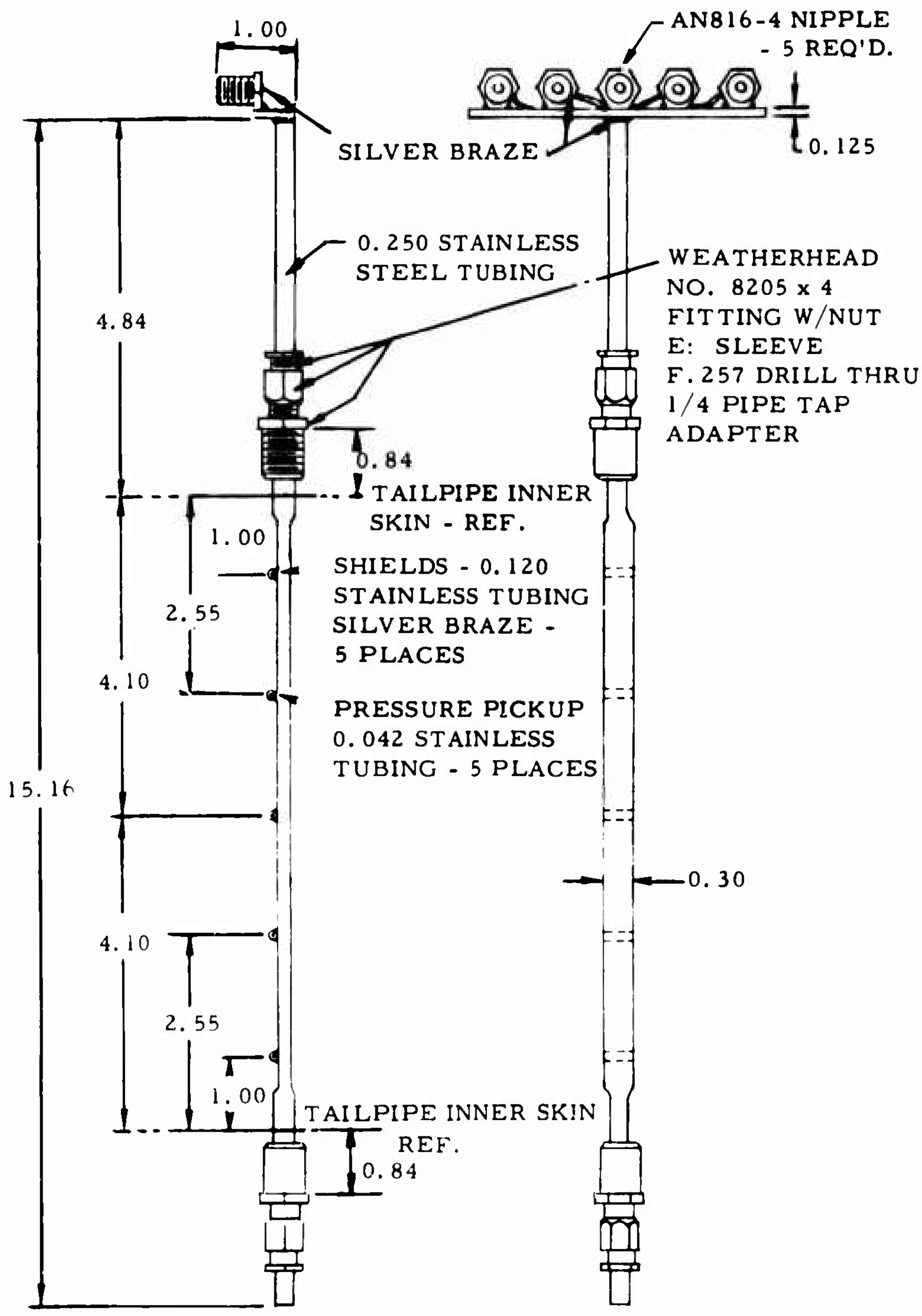


Figure 93. Exhaust Gas Total Pressure Rake.

The Cox meter was used as the only flow-measuring device on the engine test of the emulsion, as it was felt that the erratic performance noted in the laboratory could be detected by observing the oscillograph. A study of the data on the engine test run of the emulsion immediately indicated a large deviation in fuel flow between the JP-4 calibration run and the emulsified fuel test without the attending changes in exhaust gas temperature and engine thrust. The fuel tank was then removed from the fuel cart and placed on a large precision scale. The balancing adjustment arm on the scale provided a convenient method of accurately subtracting a 10-pound weight increment. A reading was then established on the scale dial and the timer was started. The weight was restored to zero, and the timer stopped as the scale dial came back to the initial reading.

This simple, elementary method provided acceptably accurate fuel flow data for the feasibility demonstration with the gelled fuels as the remaining data points indicate. The timed-weight method was subsequently used to calibrate the transient data recorded on the oscillograph. Duplicate data were taken on each steady-state point, thus establishing a comparative calibration. These points are shown plotted in Figure 94. These data substantiate the previous evidence that the fuel flow recorded on the emulsion test run was about 8 to 12 percent higher than the actual fuel flow. The previous emulsion data were then corrected using the JP-4 calibration.

The turbine type flowmeter is a convenient method of measuring fuel flow. A study should be made, however, to increase its accuracy and reliability when measuring gelled or emulsified fuels in order to provide the necessary laboratory instrumentation for future work on these promising fuels.

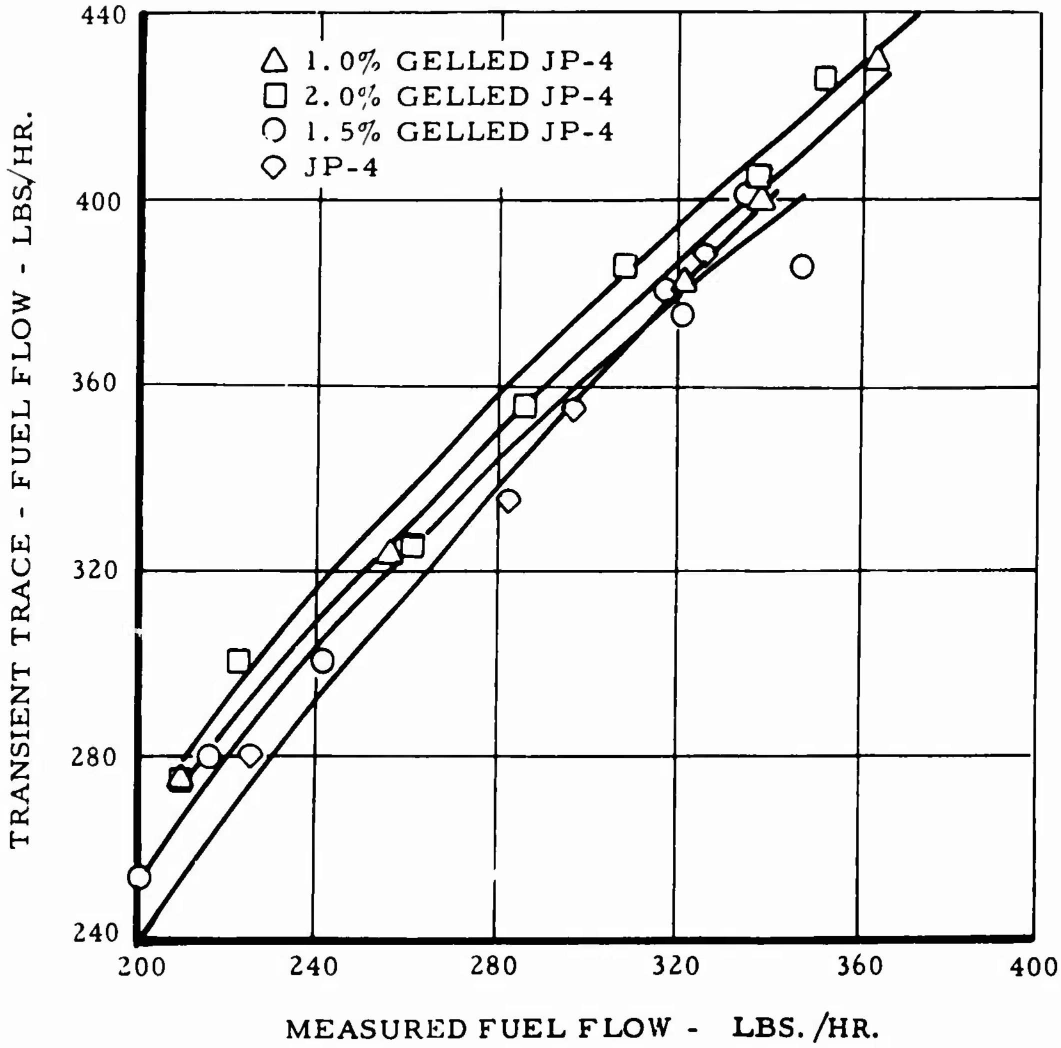


Figure 94. Transient Fuel Flow Calibration.

LABORATORY TESTING

LABORATORY TEST OBJECTIVE

The object of the laboratory investigation was to become familiar with the general flow characteristics of the fuels and to determine the effectiveness of the complete engine fuel system using gelled and emulsified fuels. This was to be accomplished by evaluating the present system components. In the event of unsatisfactory operation, the components would be altered as indicated, except for the fuel control, where a manual system would be substituted. A manual fuel control would be worked out in a logical step-by-step sequence. No consideration was given to operation at other than normal ambient conditions.

LABORATORY TEST PROCEDURE

The mixing, simulated vehicle tankage and vehicle fuel delivery system in the form of a portable test rig, Figure 95, was supplied by a subcontractor. The gelled fuel was prepared in volumes

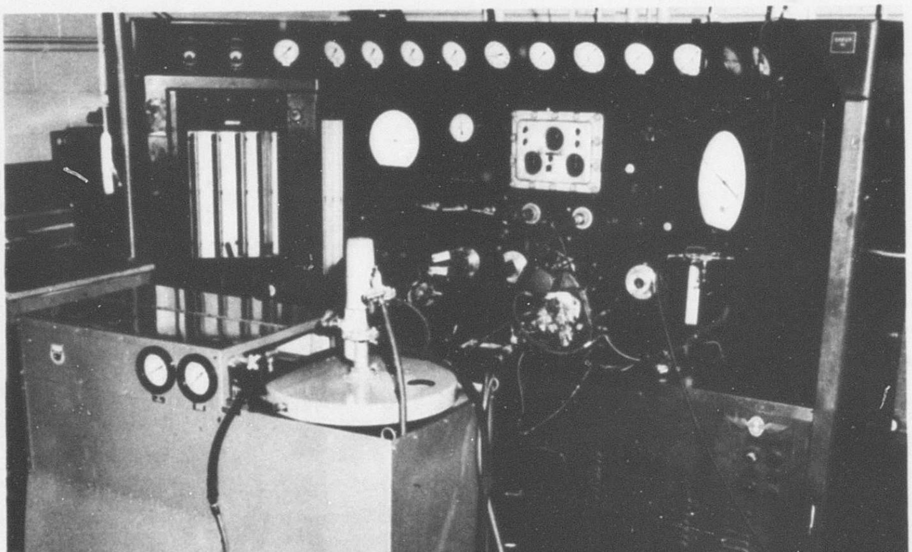


Figure 95. Portable Fuel Rig.

of 30 to 45 gallons at a time. The method of preparation involved adding the correct volume of a proprietary alkylamide gelling agent to the JP-4 fuel. The mixture was heated to approximately 135°F to cause the agent to go into solution. The emulsified fuel required no heating and was initiated with a seeding solution, also proprietary. The seeding solution was introduced to a limited amount of JP-4 fuel, and the mixture was passed through a shearing pump to emulsify the two components.

The fuel preparation stand consisted of an epoxy-plastic-lined 55-gallon drum for a tank and the necessary heaters and pumps for manufacturing both types of fuels. A modified commercial pneumatically powered grease pump using a rubber-sealed follower plate was used to pump the gelled and emulsified fuels. The amount of fuel boost pressure required at the turbine-engine-driven fuel pump was regulated and controlled by a suitable adjustable system contained within the fuel stand.

The laboratory phase consisted of initially experimenting with the flow characteristics of the two types of fuels: 2-percent gelled JP-4 and emulsified JP-4 fuel. The fuel system was connected to the test-bench-mounted engine fuel pump. The discharge flow from the engine pump was observed flowing down a clear plastic sheet. A series of pictures serves to illustrate the flow characteristics of the three types of fuels. Normal JP-4 is shown in Figure 96. Identical flow conditions are illustrated in Figure 97, demonstrating the characteristics of the 2-percent gelled JP-4 fuel. The applesauce-like quality of the material is readily apparent from the photograph. The emulsified JP-4, again under similar flow conditions, is shown in Figure 98. The material tends to recombine quickly after being chopped by the two preceding pumps and remains as a glassy rod-like cylinder as it slides down the plate. It can be observed that the cross section of the cylinder has very little distortion as it slides down the plastic sheet.

Data taken at this stage of the testing indicated the flow resistance and characteristics to be very similar to JP-4; therefore, it was decided to attempt operation in the engine fuel control. The fuel control was mounted on the laboratory test bench, which is capable of simulating steady-state engine operation while measuring the control performance, Figure 99. The fuel control operated successfully using both the 2-percent gelled fuel and the emulsified fuel without modification, as illustrated in Table V.

Figure 96. Flow of JP-4 Fuel.

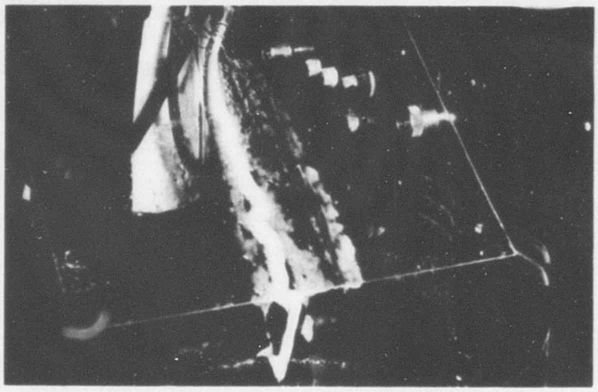


Figure 97. Flow of 2-Percent Gelled JP-4.

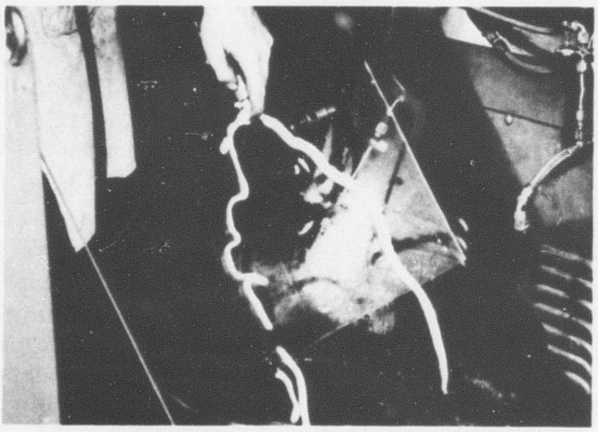


Figure 98. Flow of 97-Percent Emulsion of JP-4.

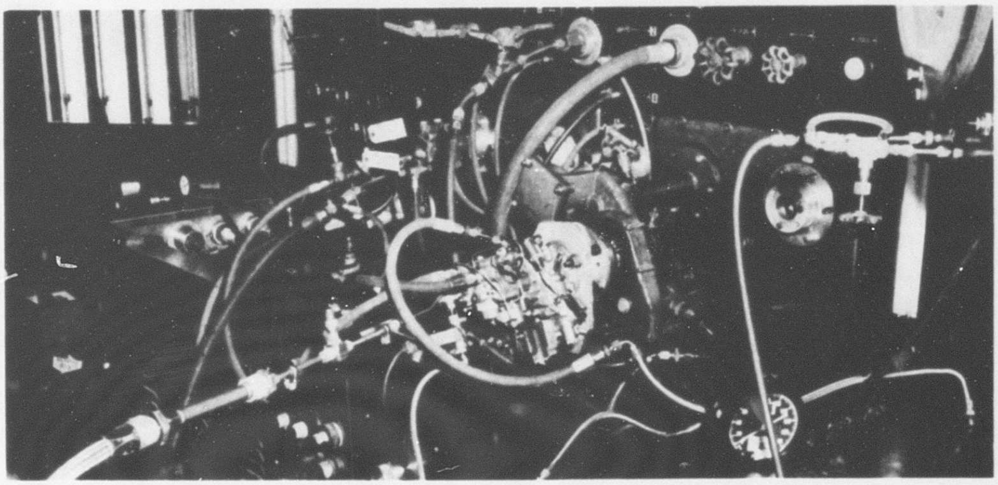


Fig. 99. Engine Control Mounted on Test Bench.

TABLE V

FUEL CONTROL CALIBRATION

Drive Speed	Compressor Pressure	Calibrated Fuel Flow (Lbs./Hr.)				
RPM	In. Hg. Abs. Hg.	7024A Type II Calibration Fuel	2% Gelled Fuel		Emulsified Fuel	
			Turbine EPUT	Volume Measure	Turbine EPUT	Volume Measure
1000	38	76.5	73	73		78
2600	79.6	218	217-222	214	191-200	212
3000	105.6	292	294-296	282	290	282
3600	167.2	443	442-443	438	424-428	414
*3900	198.2	257.5	303-305	288	286-289	303

*Governor Check

The control was judged to be in calibration within normal standards and was ready for engine feasibility testing. The fuel distributor was then evaluated using both fuels. The fuel distributor's flow characteristics were judged to be normal in all respects.

An operating mockup of the complete engine fuel system was completed by piping the regulated or controlled flow from the control to the laboratory engine slinger test stand, Figure 100. The rotating fuel slinger is an important feature of the aviation gas turbines manufactured by Continental. The slinger rotating at shaft speed is used to atomize or break up the fuel into the small micron-sized particles required for efficient combustion. It was judged from the slinger test stand that the atomization of both the gelled and the emulsified fuel would be adequate for successful engine operation. The emulsified fuel recombined readily on the chamber walls to form rather large masses which collected around the drain of the test fixture.

The auxiliary starting fuel nozzles used to ignite the spray from the engine fuel slinger were then evaluated. The starting nozzles are basically conventional single-orifice swirl type nozzles used to create a torch-like flame. The spray characteristics are illustrated in Figures 101, 102, and 103. Figure 101 is a normal spray using JP-4. The 2-percent gelled fuel is shown in Figure 102, and the emulsified fuel is illustrated by Figure 103. The tendency for recombination of the emulsion is again illustrated by the deposits clinging to the side of the open tank.

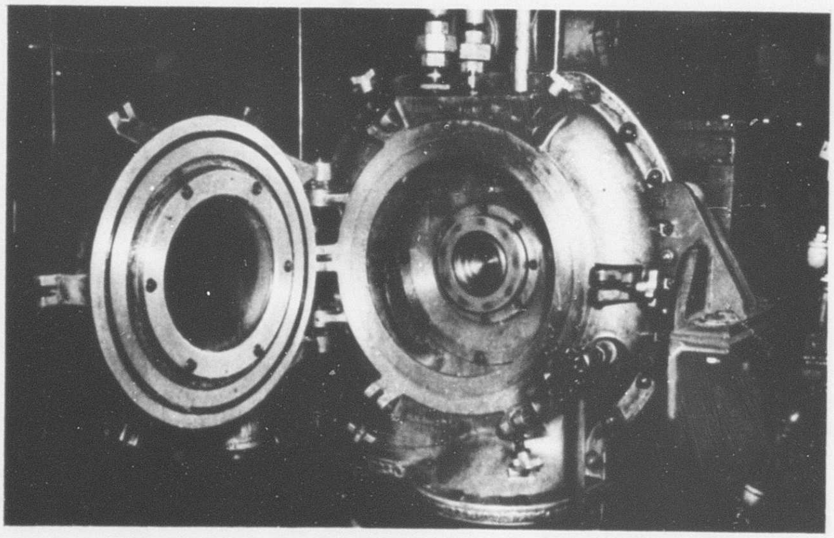


Figure 100. Laboratory Engine Slinger Test Stand.

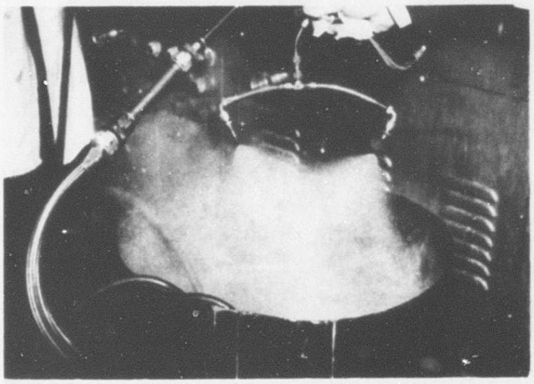


Figure 101. Starting Fuel Nozzle Spray With JP-4.

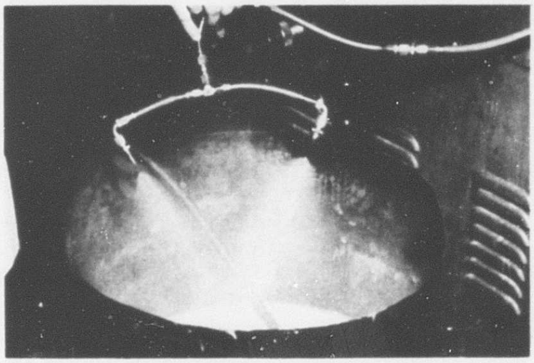


Figure 102. Starting Fuel Nozzle Spray With 2-Percent Gelled JP-4.

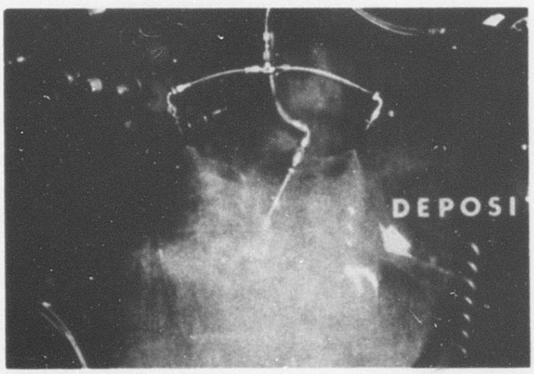


Figure 103. Starting Fuel Nozzle Spray With Emulsified JP-4.

LABORATORY TEST RESULTS

The laboratory tests demonstrated that successful control operation under normal ambient conditions could be achieved with the present engine fuel system using either the emulsified or the gelled fuel. The fuel control was capable of performing within essentially normal flow calibration tolerances while metering gelled and emulsified fuels during bench testing under simulated engine conditions. Engine auxiliary starting fuel nozzles used during starting were also found to perform in a satisfactory manner. Problems were experienced using a turbine type flowmeter with the new fuels. The calibration of the turbine flowmeter was checked using a timed-volume method, and the accuracy of the meter was confirmed. The problem was traced to fouling of the turbine flowmeter with dirt. This occurred several times, but was not recognized as a major problem at this time.

ENGINE TESTING

ENGINE TEST OBJECTIVE

The object of the engine test was to demonstrate the feasibility of directly burning gelled and emulsified fuels in a T72-T-2 gas turbine engine and to define any associated engine problems encountered. All test work was accomplished under essentially standard-day conditions. Fuel preparation, tankage, and the initial boost pumping system were provided by a subcontractor.

ENGINE TEST PROCEDURE

The T72 engine gas generator section used for the feasibility tests was calibrated for performance on JP-4 fuel before and after the series of tests. The engine was also recalibrated after being disassembled to clean the plugged fuel manifold which occurred after the 97-percent emulsion test. The engine was operated on normal JP-4 fuel after each different fuel test to flush out as much of the gelled or emulsified fuel as possible.

An emulsified fuel was the first fuel tested in the engine. A 98-percent emulsion of JP-4 prepared by the Petrolite Corporation was tested. The fuel was pumped from a 30-gallon drum by means of a laboratory centrifugal boost pump. The pump was limited to a head of approximately 25 psig. Difficulty was immediately experienced with cavitation of the main engine pump. The problem was solved by removing the laboratory paper type fuel filters which were causing a large pressure drop. Removing the filters allowed the pump to supply the necessary boost, which eliminated the cavitation. The engine successfully consumed the entire fuel supply while performing normally under the entire speed range, including several starts and stops, for a total of over 23 minutes running time. The newness of the fuel and the short duration of the test limited its value to merely demonstrating the feasibility of using this type of fuel.

The engine was next operated on a 97-percent emulsion, conforming to contract specifications. The engine was operated on two successive days for a total of over 45 minutes running time. In general, the engine performance was normal, although some rough running and difficult starting characteristics were noted. These problems were later traced to a dirt contaminated fuel control, which finally caused a partially plugged fuel manifold. This condition was discovered when it proved to be extreme-

ly difficult to operate the engine on a 1.5-percent gelled fuel immediately after the plain JP-4 flushing operation following the 97-percent emulsified fuel test.

Starting proved to be difficult and normal running was impossible. Pressure measurements then indicated that the trouble was a plugged fuel manifold and an inoperative fuel control.

The engine was disassembled and the fuel manifold reverse was flushed. An analysis of the dirt indicated a predominant amount of rust with other ordinary contaminants. The control was partially disassembled and cleaned. Large amounts of rust and dirt were found throughout the control. Also worthy of note is the fact that, in the large area surrounding the three-dimensional cam system, a large amount of 97-percent emulsion and 1.5-percent gel was found unmixed but compacted together. The internal strainer in the control was plugged and lodged with rust in the bypass position. The engine compressor diffuser was replaced during the engine inspection and assembly.

A series of tests on available filters with the 1.5-percent gelled JP-4 provided some interesting information. Filters of less than 40 microns tended to squeeze the JP-4 from the gelled fuel, leaving a residue with an increased amount of gelling agent next to the filter. The residue rapidly increased in the percent of gelling agent until it became almost plastic, very similar to the light skim that forms on the top of an open can of varnish. Filters of approximately 100 microns proved to be successful, although it should be stressed that only short runs were accomplished.

Two filters were then installed on the engine. A metal 100-micron large mesh strainer was provided immediately before the fuel manifold and a large 100-micron porous-metal air-line type filter was installed ahead of the engine control.

Batches of 1- and 1.5-percent gel were prepared and remained in storage in semiclosed 55-gallon drums for a period of 3 weeks. Attempts to run the engine on either batch of fuel were completely unsuccessful. The problem was traced to hard spots in the gelled fuel. Examination of the fuel indicated stringy concentrations of the gel in each batch. The two engine primer nozzles became plugged, but were easily cleaned by heating, thus melting out the gel concentration.

A fresh batch of gel was mixed and an initial start was made on the old gel from the previous run. Fuel pressure gages indicated the filters to be plugged. The engine was stopped and the filters were cleaned. The engine was then started on fresh gel, and it ran continu-

ously for 51 minutes while steady-state and transient data were recorded. The engine was then flushed out with JP-4 for further testing.

A fresh batch of 98-percent emulsion was then tested for a total of 49 minutes, including engine idling at 30,000 rpm, acceleration, and steady running at various speeds.

Starting difficulties were next experienced while attempting to test the 1-percent gelled fuel.

The fuel control bypass valve, Figure 104, was found to be remaining in the open position after shutdown. Thus, it was impossible to create the proper pressure head across the metering orifice. It is believed that this problem resulted from a restricted vent opening above the valve diaphragm. Subsequently, it was found that the valve could be made to seal for a normal start by striking the housing with a light hammer.

The engine was then started normally and the 1-percent gelled fuel test was completed in 34 minutes of running time. The engine was stopped and allowed to cool for 1 hour and 15 minutes. A completely normal start was then made, and the engine operated for an additional 20 minutes to consume the remaining fuel.

A complete calibration run was then made using JP-4 to determine if any significant change occurred in the engine.

The engine was completely disassembled for inspection; Figures 105 and 106 illustrate the excellent deposit-free condition of the outer and inner combustor shells. Examination of the entire hot section of the engine proved that all parts were in normal condition; there was no evidence of difference from running with the different test fuels. The turbine nozzles and wheels were also deposit free and completely normal in all respects. The same igniters were used throughout the entire series of tests. Primer nozzles were changed during the gelled fuel testing, before a cleaning procedure was established.

The fuel control was also disassembled for inspection. The internal housing cavity was completely filled with a relatively thick gel, Figures 107 and 108. The pressure regulating or bypass valve, Figure 104, was found to have a rather hard gel solution surrounding the diaphragm. This condition together with the relatively small vent holes was probably responsible for a large share of the fuel control problems.

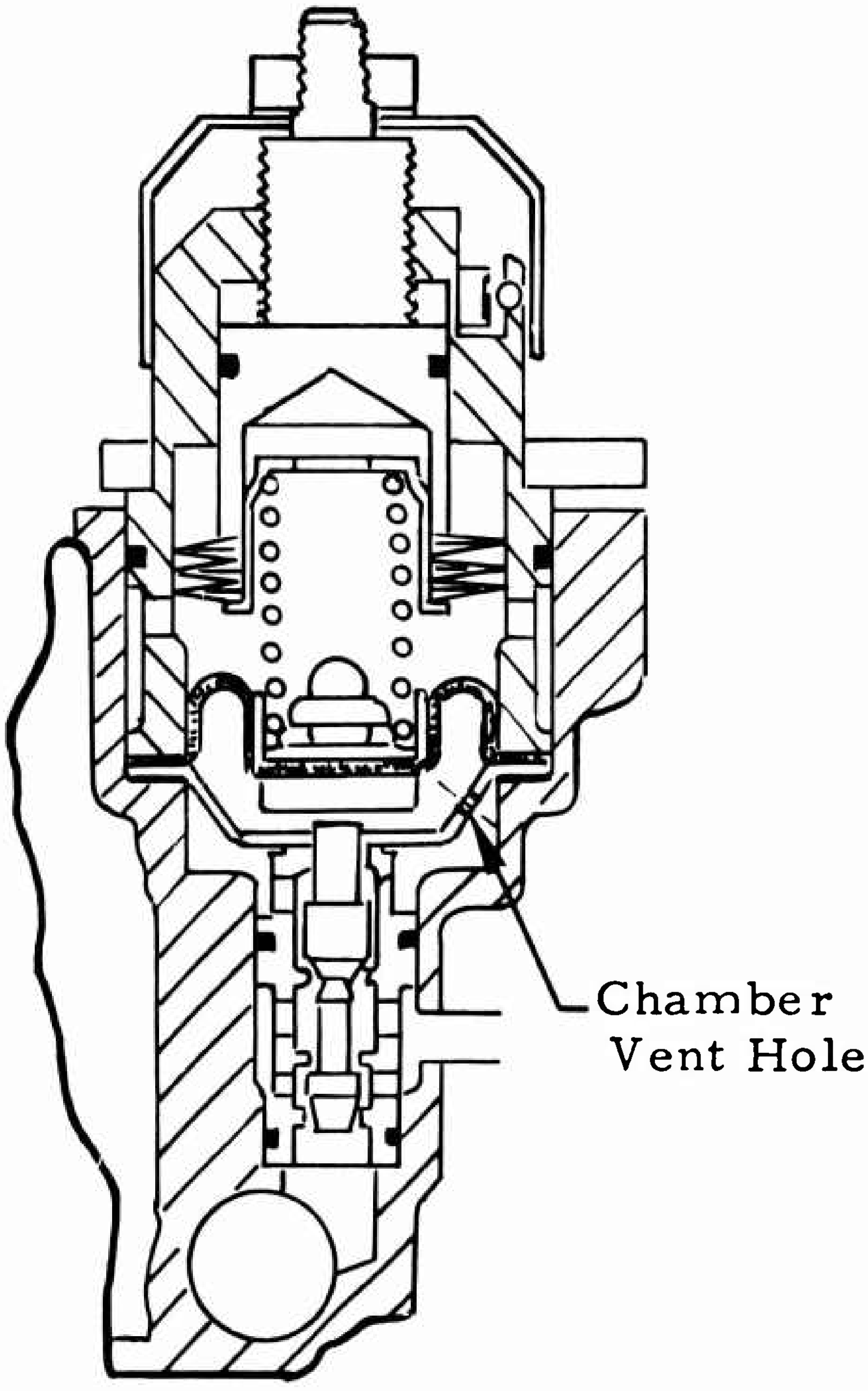


Figure 104. Fuel Control Bypass Valve.

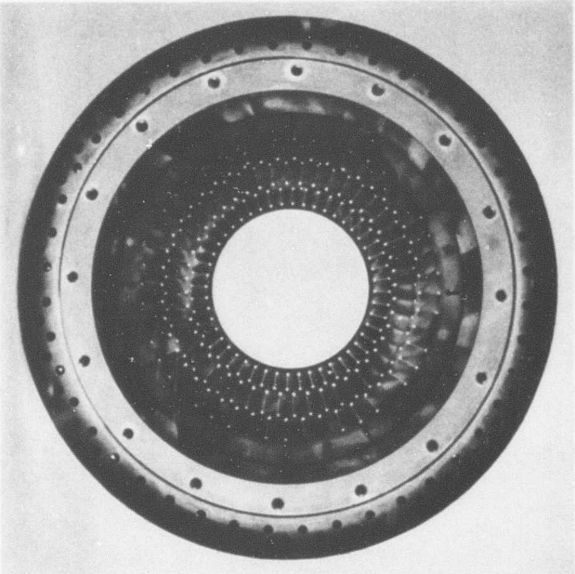


Figure 105. Outer Combustor Shell.

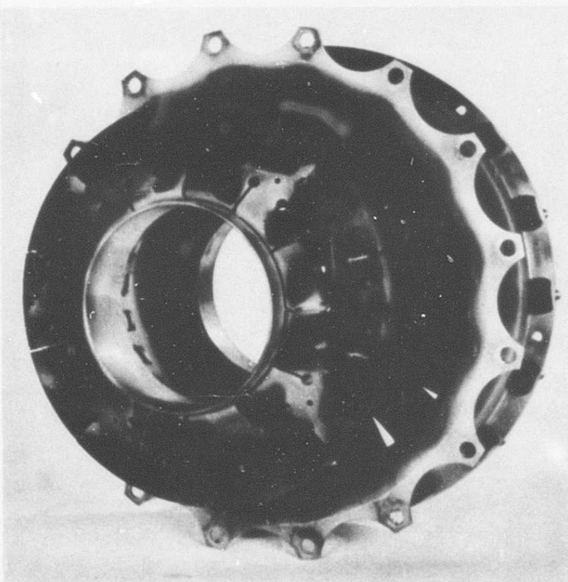


Figure 106. Inner Combustor Shell.

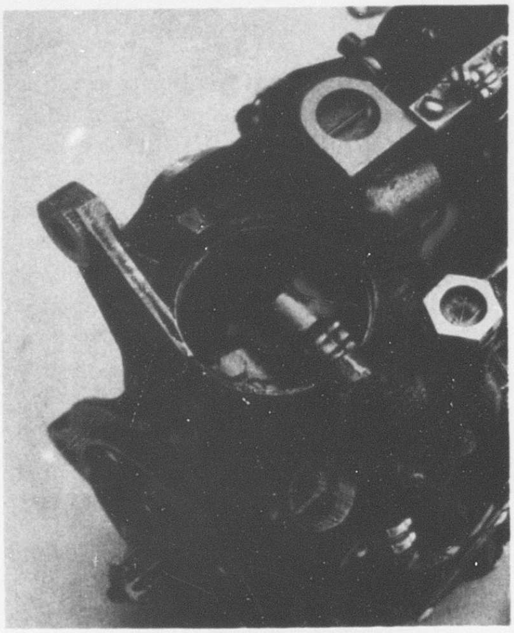


Figure 107. Fuel Control Cavity.

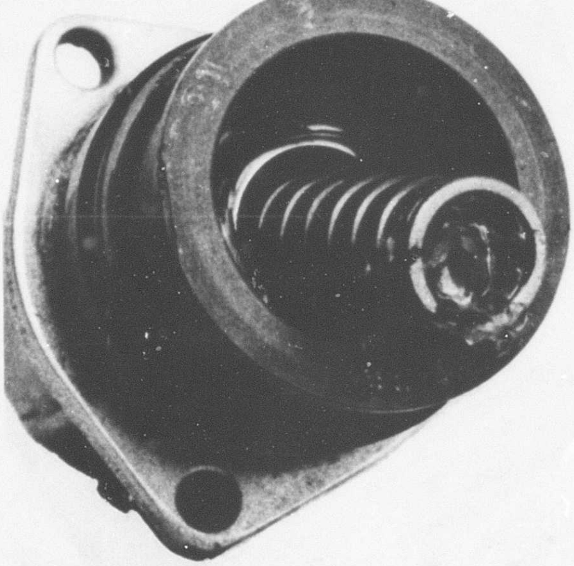


Figure 108. Fuel Control Spring.

ENGINE TEST RESULTS

Steady-state and transient data were taken during each of the different fuel tests to determine engine performance. All data were conventionally reduced and corrected to standard-day conditions. The test facility used was a turboshaft test cell; therefore, a direct means of measuring engine thrust was not available. Thrust was computed based on airflow, exhaust gas total pressure, and exhaust gas total temperature. The basic steady-state performance parameters such as pressure ratio, airflow, exhaust gas temperature, fuel flow, and thrust have been plotted versus engine speed. In general, it can be concluded that there is very little difference in performance for any of the fuels used.

The engine pressure ratio is shown in Figure 109. It should be noted that the two high-flow lines represent the JP-4 calibration run and the emulsion test following the calibration run. The engine was subsequently disassembled to clean the fuel manifold, and also at this time a new radial diffuser was installed which resulted in a reduction of the pressure ratio and airflow. The difference in airflow is shown in Figure 110. The data for the JP-4 calibration and the following emulsion test show good agreement. The remaining data representing the latter assembly are also in close agreement except for the JP-4 calibration run following the engine reassembly after cleaning. It is speculated that the airflow deviations may have been caused by a loose manometer line, which was tightened on a post-test inspection.

The exhaust gas temperature versus engine speed curve, Figure 111, shows that the data from the tests with gelled and emulsified fuel are completely bracketed by the three JP-4 fuel calibration runs. Thus, in this case any differences due to the type of fuel are within the data scatter between the calibration runs. The data scatter is generally $\pm$ 12°F or approximately $\pm$ 1.2-percent deviation at a mean temperature of 1000°F.

The plot of the engine thrust data is also closely grouped (Figure 112). The slightly greater airflow of the emulsified fuel test and its corresponding JP-4 calibration run is noticeable in the higher thrust points of the grouping. The engine thrust was computed based on the measured engine airflow, the exhaust total pressure, and the exhaust total temperature survey. The computation involves five separate variables, each of which represents a weighted average of multiple readings.

Engine fuel flow versus engine speed, Figure 113, also shows a consistent trend of very little deviation in the data considering the

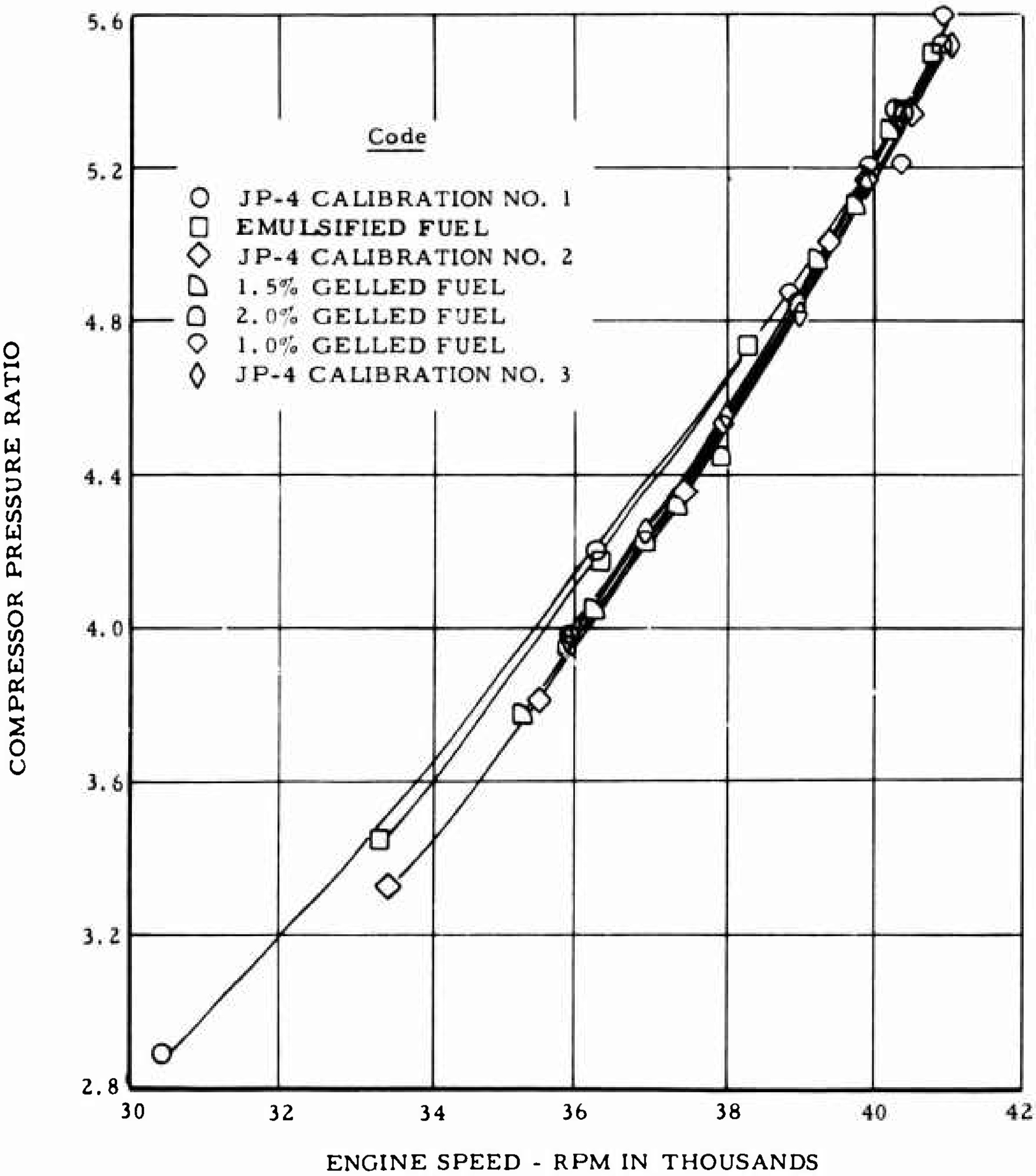


Figure 109. Effect of Gelled and Emulsified Fuel on Engine Compressor Pressure Ratio.

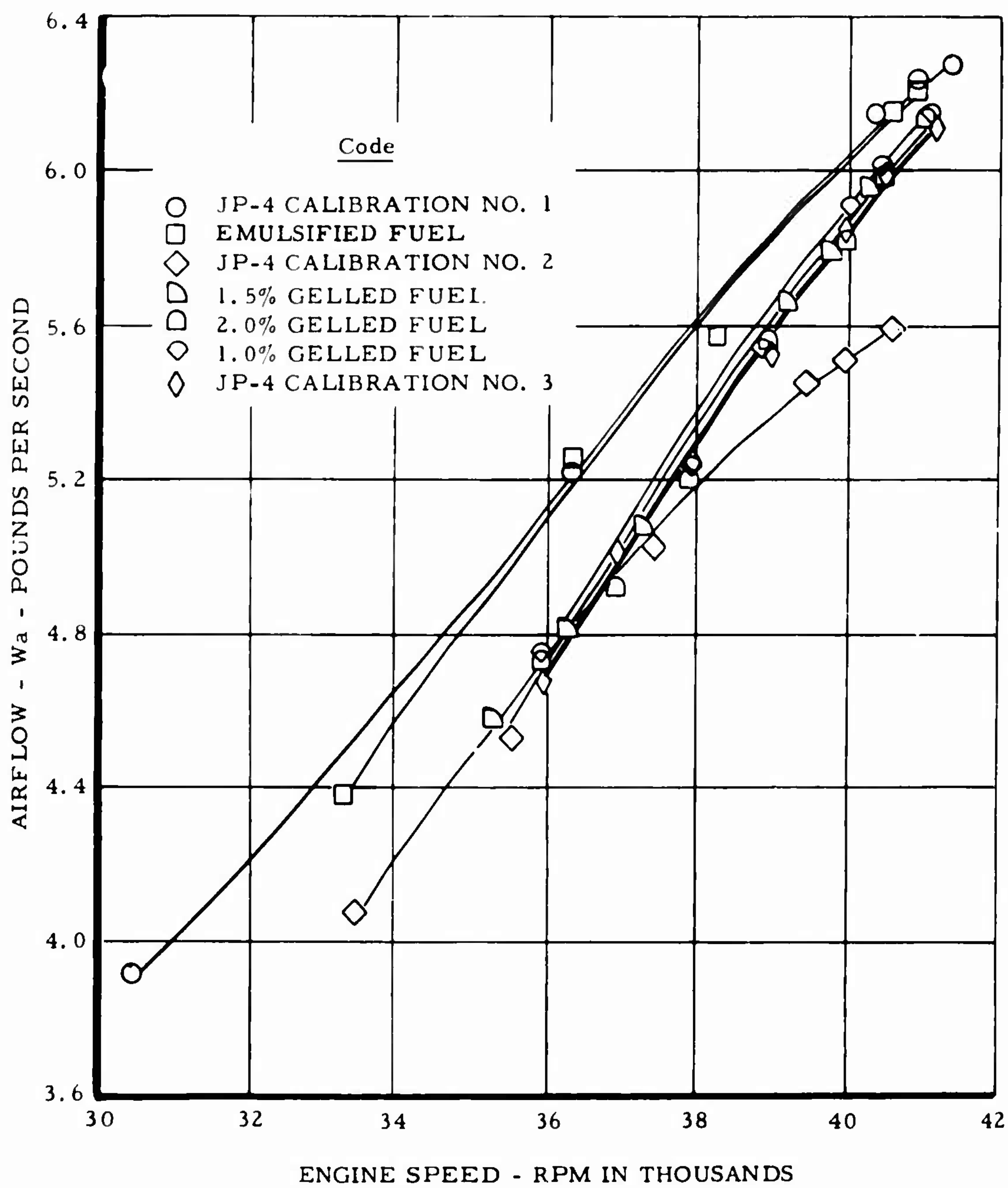


Figure 110. Effect of Gelled and Emulsified Fuel on Engine Airflow.

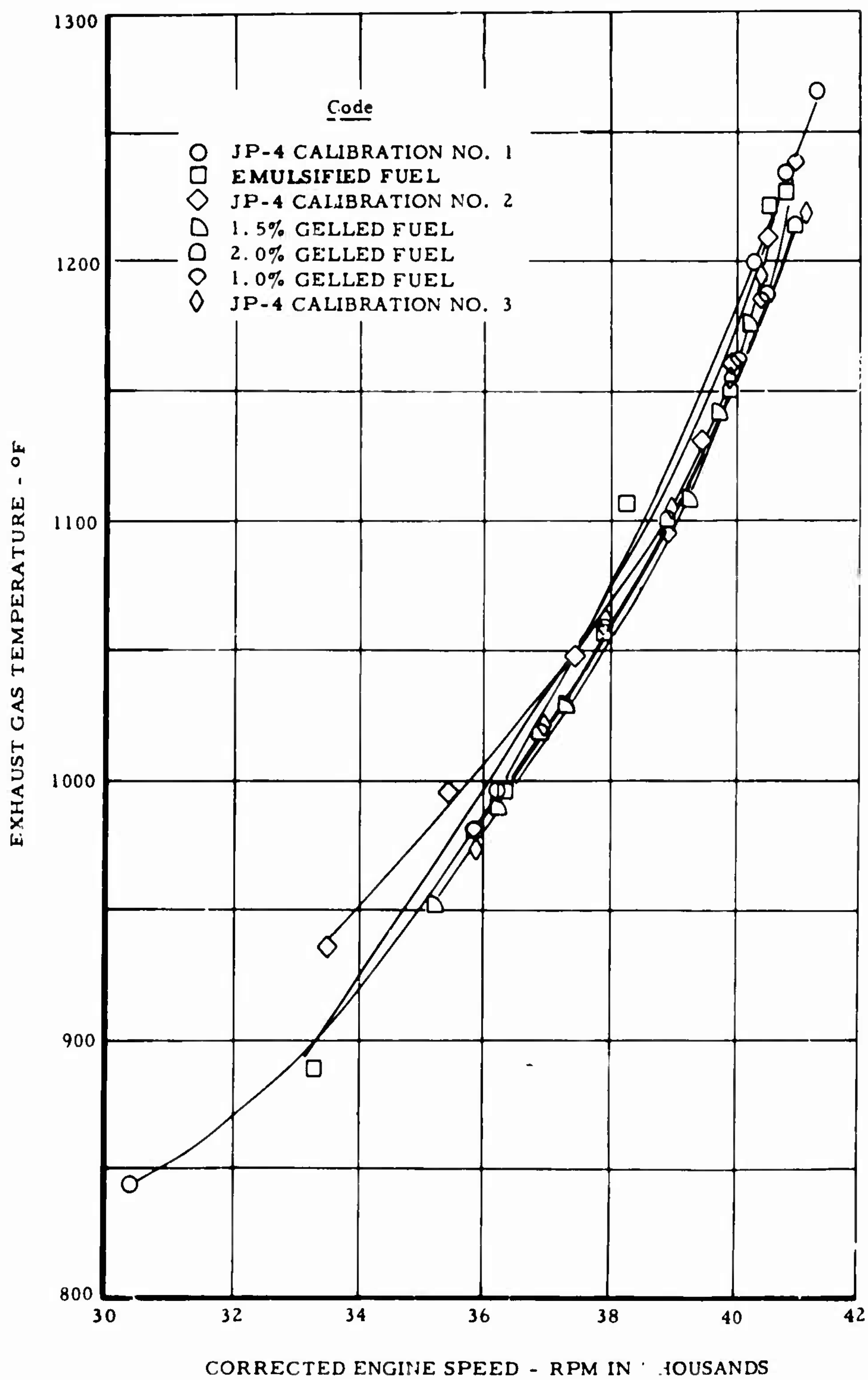


Figure 111. Effect of Gelled and Emulsified Fuel on Engine Exhaust Gas Temperature.

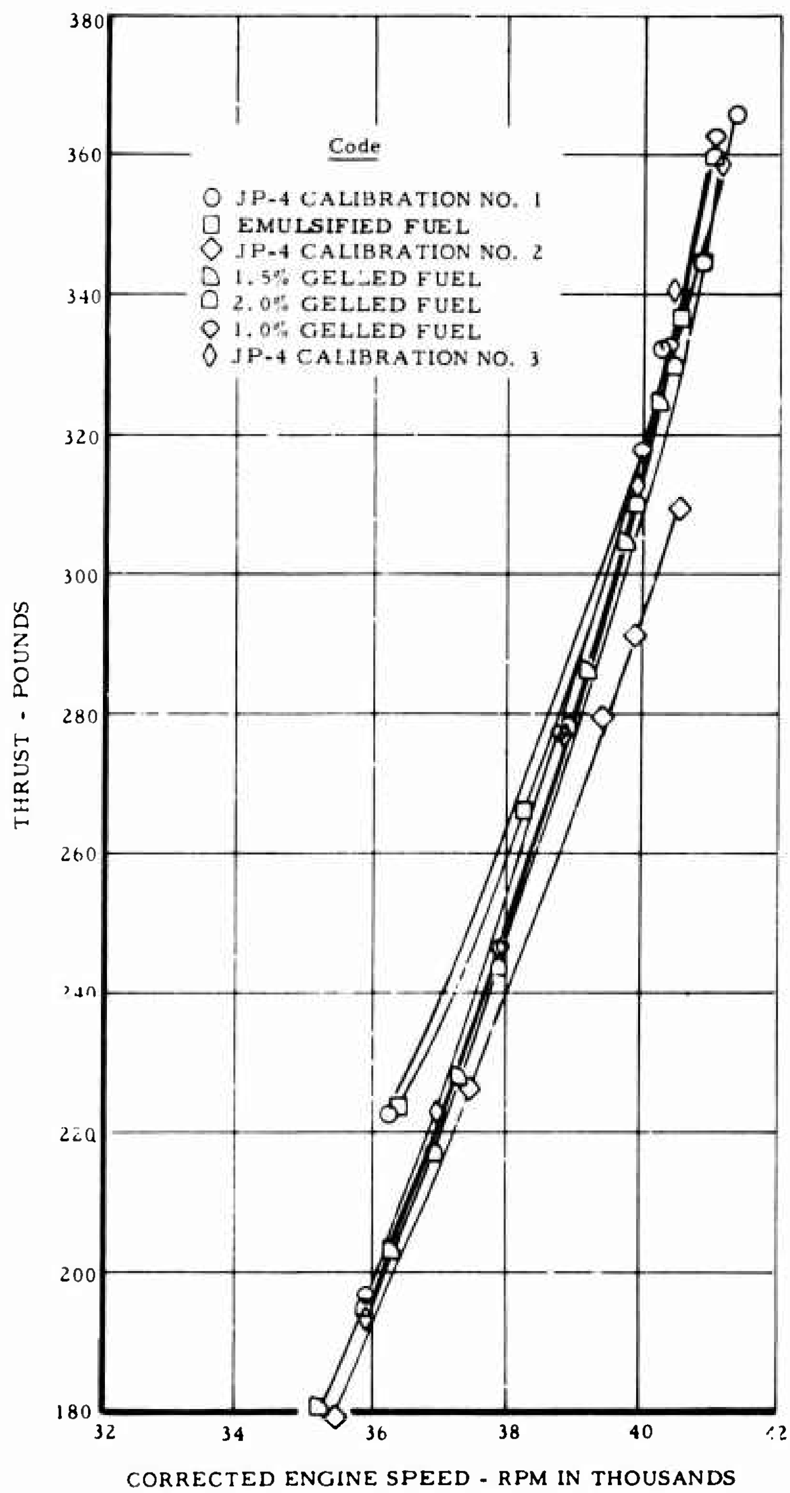


Figure 112. Effect of Gelled and Emulsified Fuel on Engine Thrust.

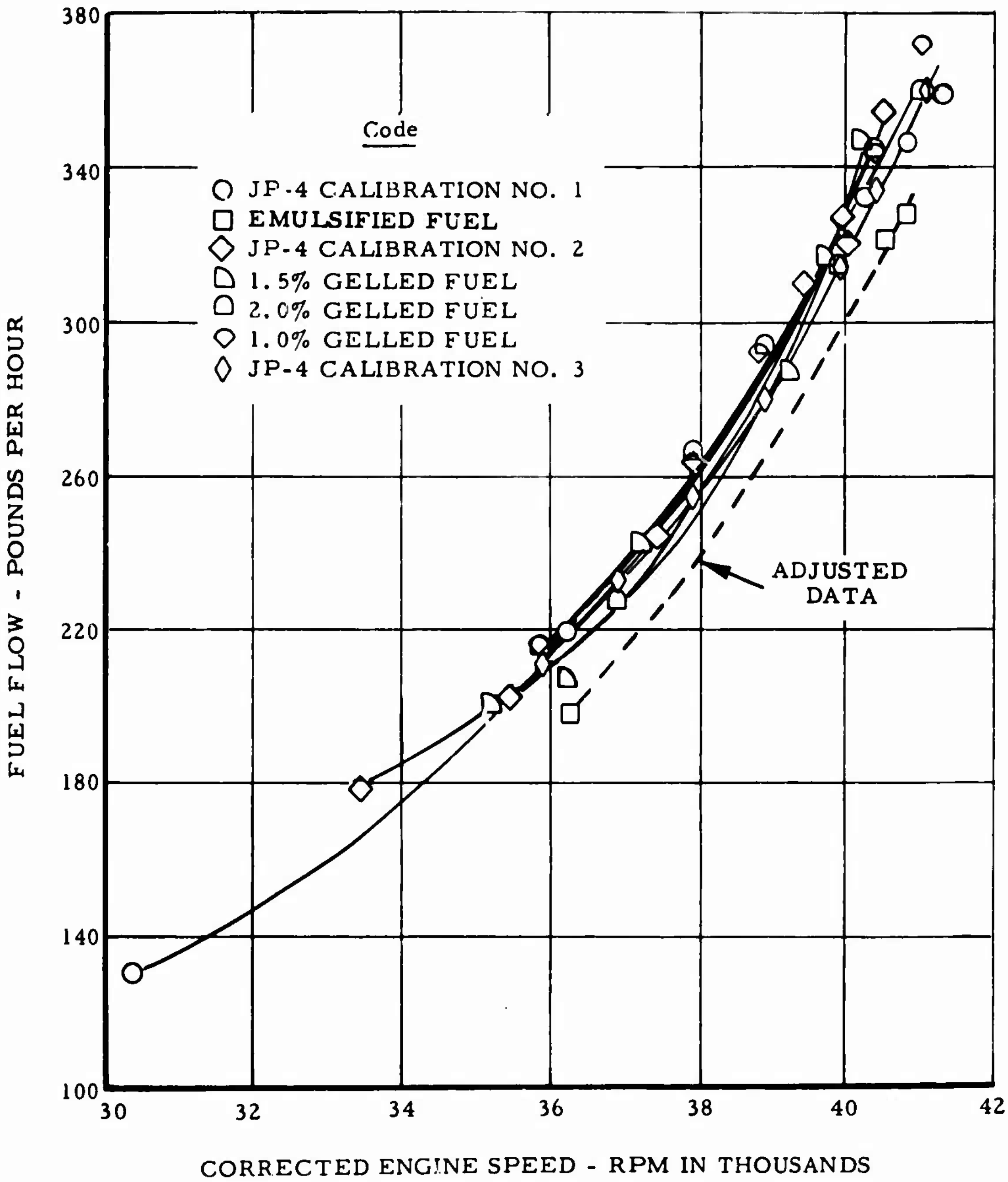


Figure 113. Effect of Gelled and Emulsified Fuel on Engine Fuel Flow.

method used for measurement. All points except the corrected data from the emulsion test represent a timed weight method of obtaining fuel flow. The data for the emulsion test were recorded with the flowmeter and subsequently corrected using the calibration obtained with the JP-4 as discussed in the instrumentation section of this report.

The test results obtained indicate no gross changes in engine performance resulting from use of the test fuels. However, it is not possible to determine minor changes due to the fuel flow measurement method required. The limited scope of the present program (feasibility demonstration) did not warrant more elaborate instrumentation, and the engine rebuild during the program, due to fuel manifold contamination, makes direct detailed performance comparisons difficult.

Starting, in general, consistently proved more difficult on the gelled and emulsified fuels. It is presently believed that the starting problem was associated with the fuel control rather than any basic change in combustion. It was consistently noted that satisfactory ignition occurred but that a number of aborted starts indicated that the fuel control was not delivering the scheduled fuel flow for starting.

Much of the starting difficulty was finally traced to unsatisfactory operation of the fuel control bypass valve. This valve tended to remain in the open position after shutdown. It is presently believed that the malfunction was due to a small vent on the valve diaphragm which restricted the fuel flow when operating with either the gelled or the emulsified fuels. A more detailed investigation would be required for a definite conclusion. It can be stated, however, that a normal start was obtained on all fuels during the course of the tests. The primer nozzles used to ignite the main combustor were able to function using all the fuel types. They did, however, plug when repeatedly used with the gelled fuels. In general, heating the nozzle to melt the gell was all that was required to unplug the primer nozzle.

The exhaust gas average radial temperature gradients for the 97-percent emulsion of JP-4 and its comparable JP-4 calibration run are shown in Figure 114. The average exhaust gas temperature is approximately 40°F lower for the emulsion due to a slight change in speed; however, the average radial temperature gradients of the runs are nearly identical. Table VI is a summary of a 20-point temperature survey confirming the similarity of the two runs.

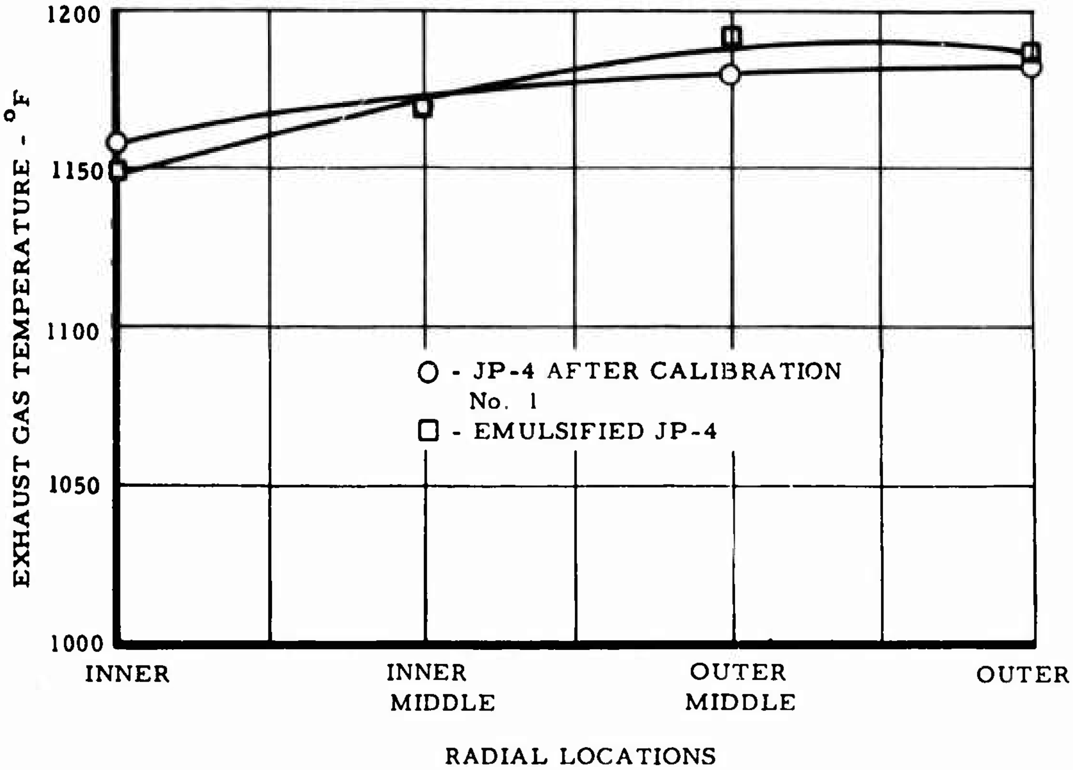


Figure 114. Measured Exhaust Gas Temperature Versus Radial Location for Emulsified Fuel.

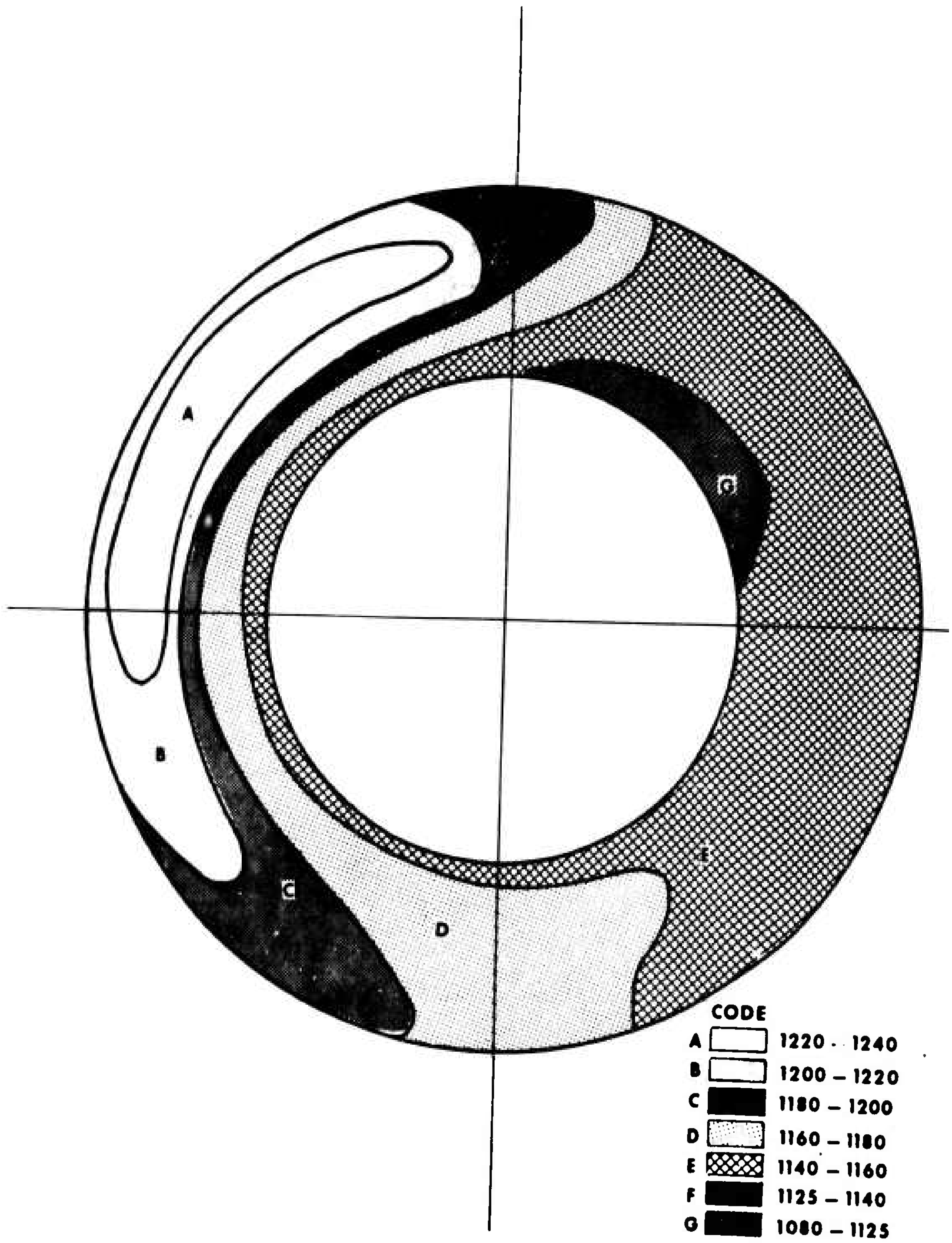
TABLE VI

TEMPERATURE SURVEY SUMMARY

Fuel	RPM	Individual Reading, °F High	Low	Diff.	Circumferential Gradient, °F
JP-4 No. 1	40,060	1240	1130	110	79
Emulsion	39,870	1190	1045	145	45

A detailed contour plot of the JP-4 calibration run is shown in Figure 115, and the emulsion contour is shown in Figure 116.

An exhaust gas average radial temperature gradient plot of the gelled fuel tests and their corresponding JP-4 calibration is shown in Figure 117. The gelled fuel runs are also closely grouped, indicating very little difference in exhaust temperature gradient. A slight deviation can be noted for the 1- and 2-percent gelled fuel. This minor deviation is further illustrated by Table VII.



Exhaust Gas Temperature Contour JP-4 Calibration No. 1.

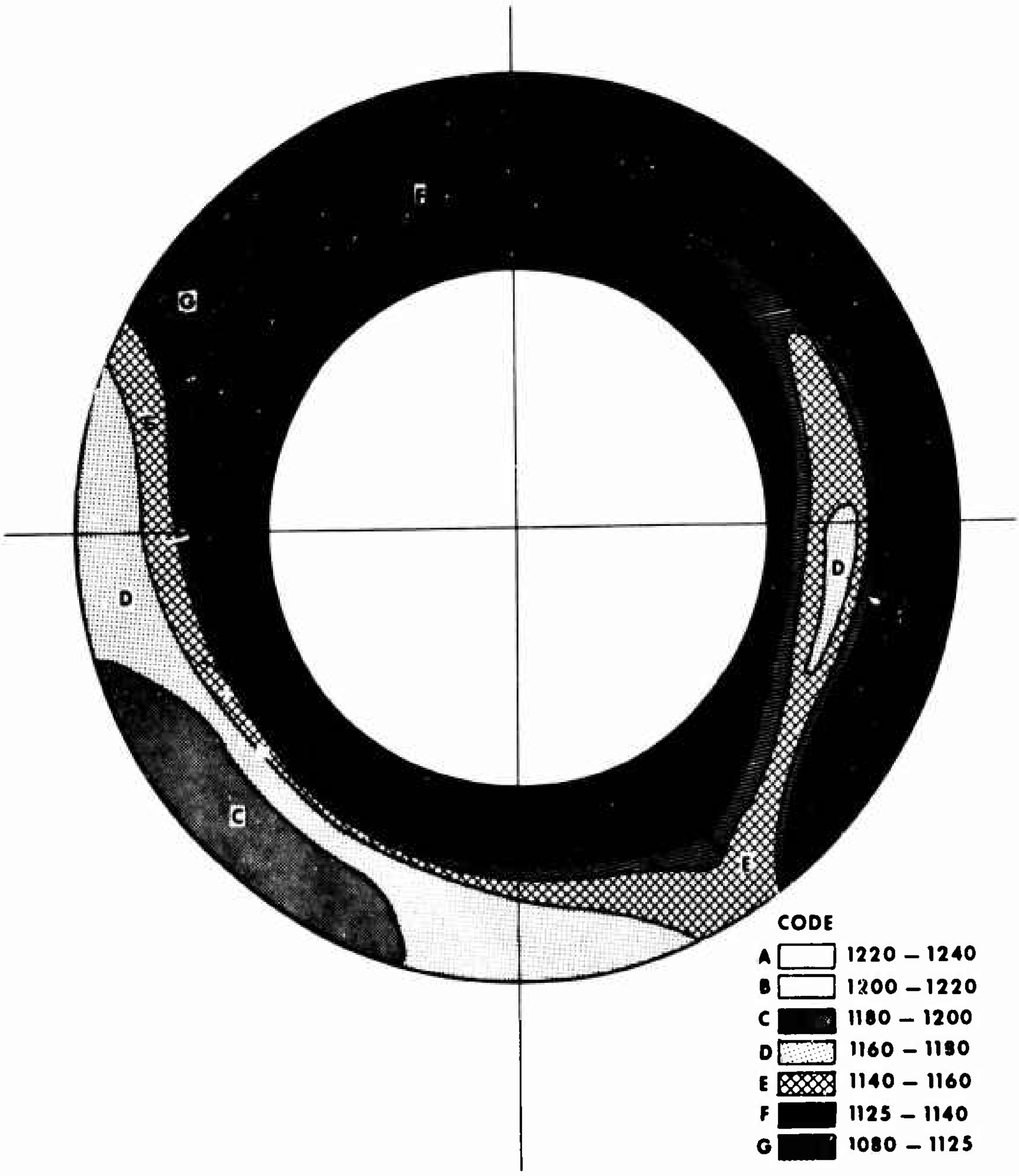


Figure 116. Exhaust Gas Temperature Contour 3-Percent Emulsified JP-4.

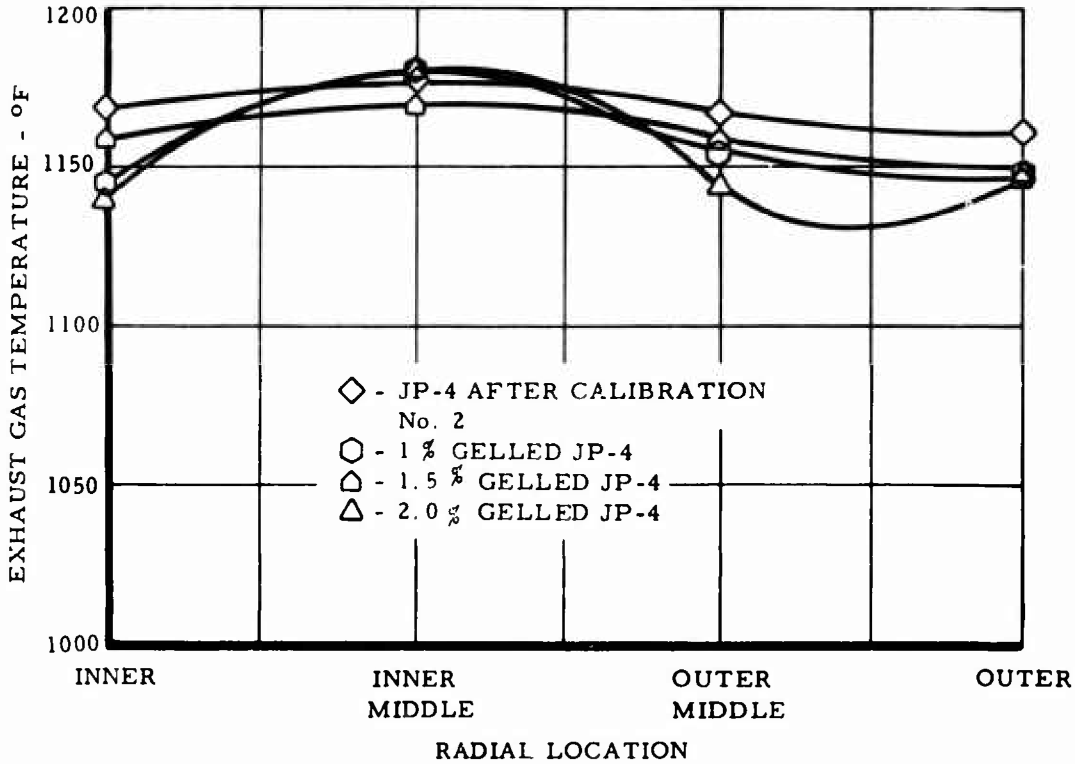


Figure 117. Measured Exhaust Gas Temperature Versus Radial Location for Gelled Fuel.

TABLE VII

EXHAUST GAS TEMPERATURE SUMMARY

Fuel	RPM	Individual Reading, °F High	Low	Diff.	Circumferential Gradient, °F
JP-4 No. 2	40,020	1200	1140	60	40
1.0% Gel	40,035	1220	1070	150	113
1.5% Gel	40,030	1200	1110	90	62
2.0% Gel	40,010	1220	1070	150	116

Detailed contour plots of the temperature distribution for the above test runs are presented in corresponding order in Figures 118 through 121.

All fuels tested produced acceptable temperature profiles; however, the fuel manifold or distributor should be matched to the particular fuel used for ideal operation. The acceptable results on the temperature survey further confirm that the combustor was operating normally on all the fuels tested.

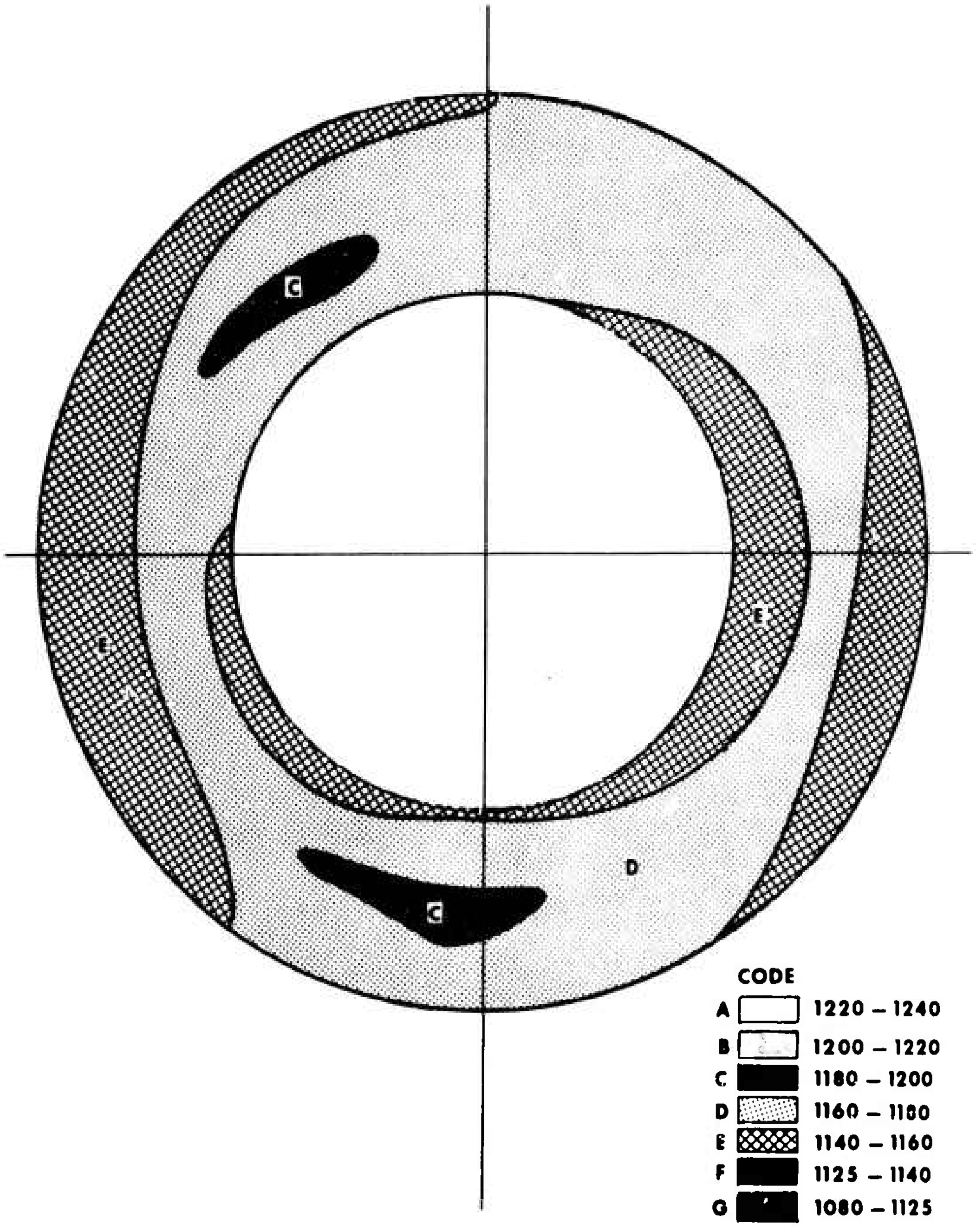


Figure 118. Exhaust Gas Temperature Contour JP-4 Calibration No. 2.

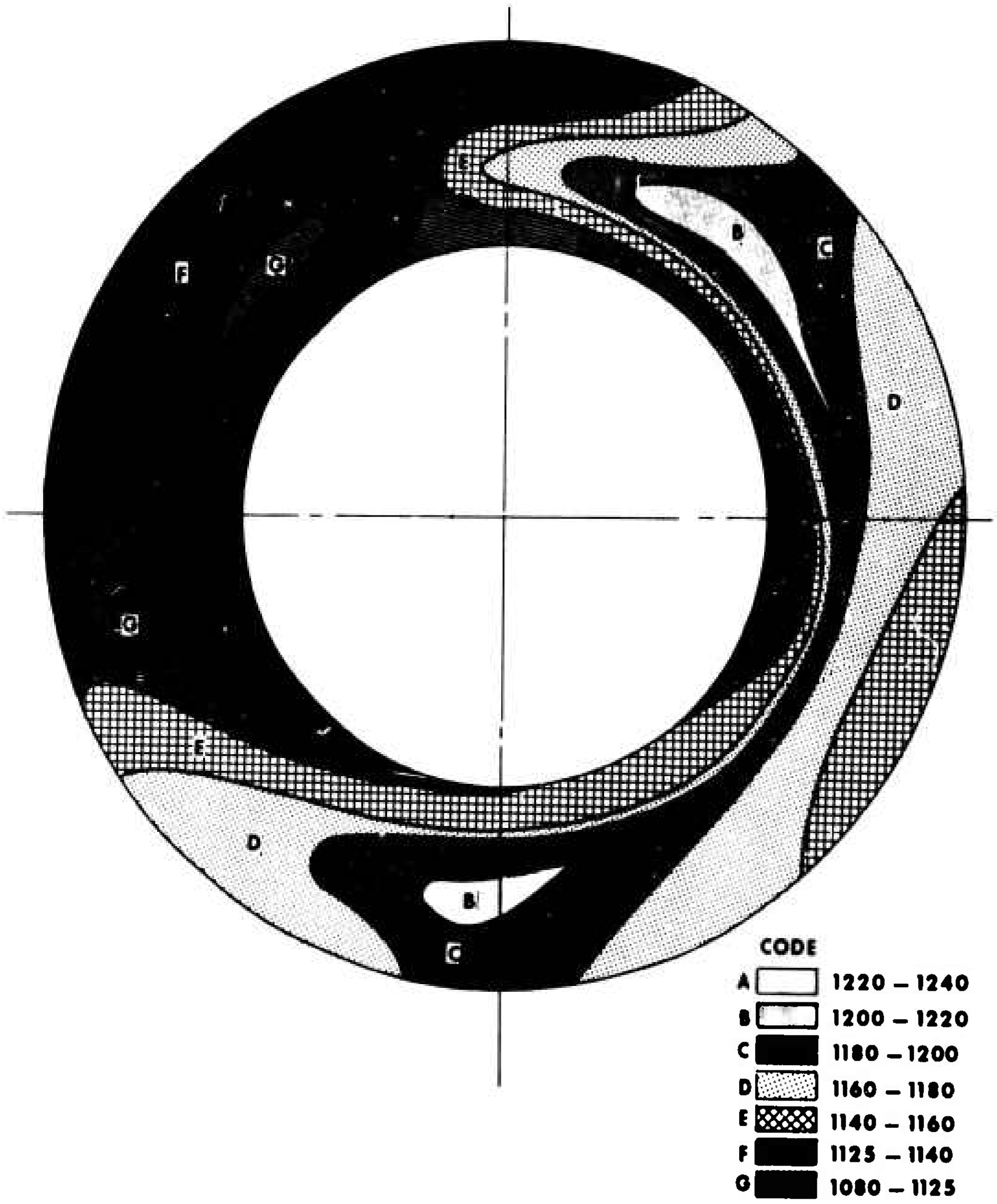


Figure 119. Exhaust Gas Temperature Contour 1-Percent Gelled JP-4.

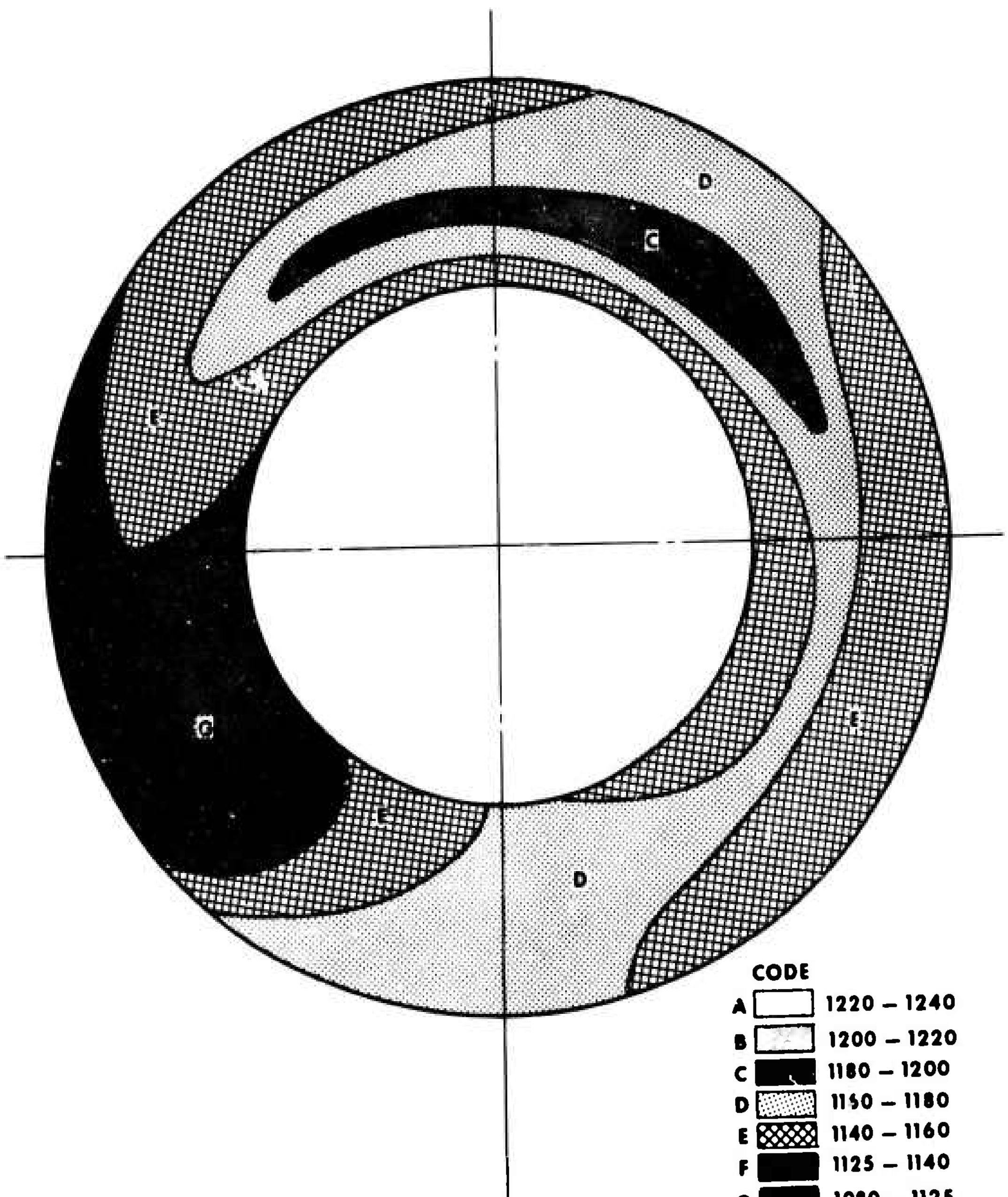


Figure 120. Exhaust Gas Temperature Contour 1.5-Percent Gelled JP-4.

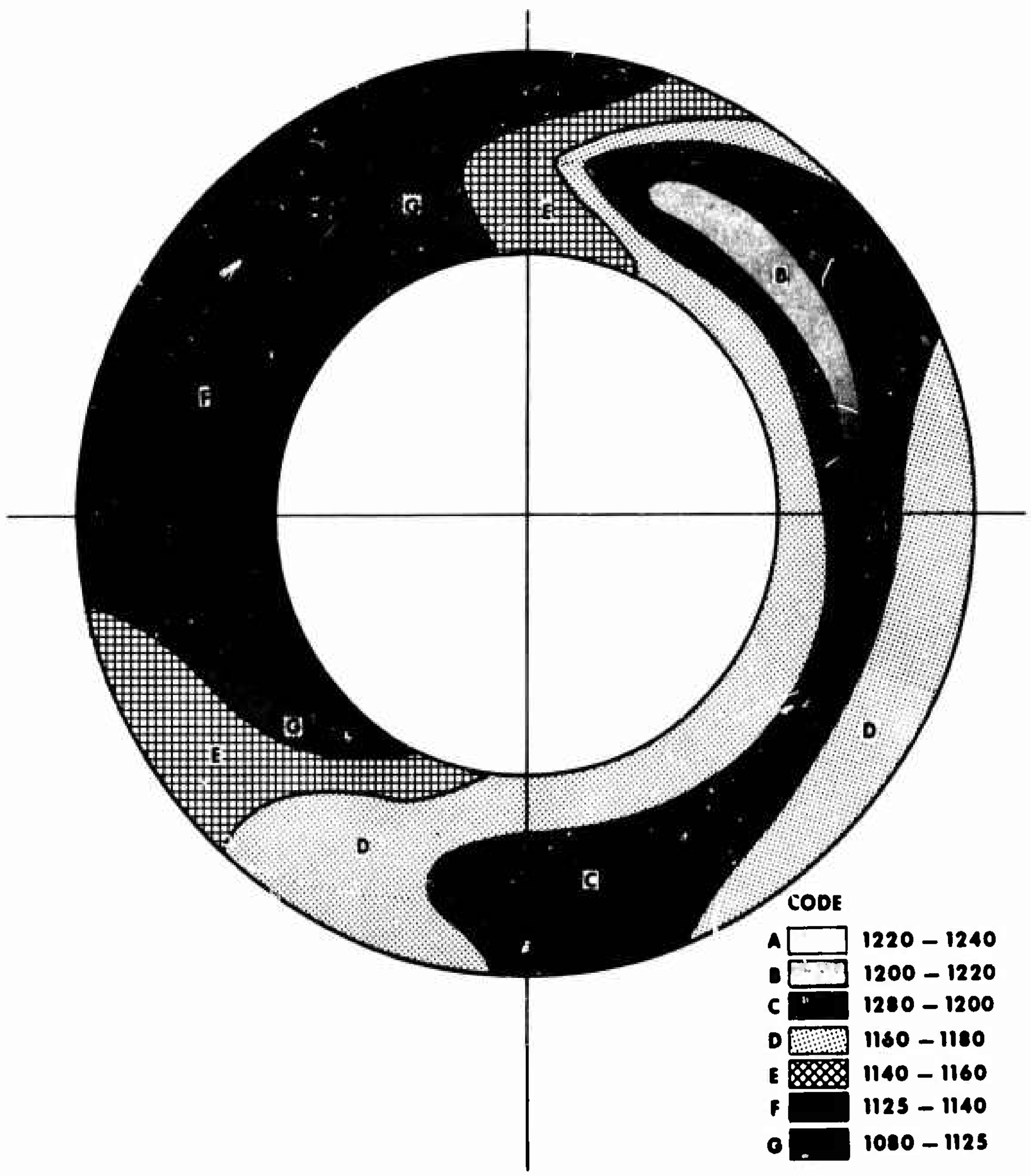


Figure 121. Exhaust Gas Temperature Contour 2-Percent Gelled JP-4.

Acceleration data taken from the oscillograph recording engine speed, fuel flow, and compressor discharge pressure versus time yielded information on the transient performance of the engine. The control used for these tests had previously been modified for use on an uprated version of the T72-T-1 engine and contained a greater acceleration fuel flow schedule than could be utilized by the engine on this program. Accordingly, it was necessary to control the engine acceleration rate by throttle movement. Thus, acceleration time is largely dependent upon operator performance, making a direct comparison of the data difficult. Fuel flow versus time for all transient data is plotted in Figure 122; a corresponding plot of engine speed versus time is shown in Figure 123.

Acceleration from approximately 32,000 to 40,000 rpm or from less than 10-percent equivalent power to 100-percent equivalent power was accomplished in less than 6 seconds. The emulsified fuel was the slowest on acceleration. Acceleration on the gelled fuels can be characterized as faster than the normal JP-4 calibration runs; also, in the case of the gels, the flow rate of the gelled fuel accelerated faster than the corresponding JP-4 calibration run. Summarizing the acceleration data, it can be stated that differences in acceleration rates were found, but at this point it is only speculation as to whether the differences represent changes in engine operation or were caused by changes in the operator's rate of movement of the fuel control lever. In either event, the rates noted were reasonable and comparable to similar JP-4 calibration runs.

Fuel Analysis

A number of tests were run to determine the gross heating value of the various fuels used. The testing was carried out by using calorimeter methods at an independent testing laboratory. The following is a tabulation of the fuels and the resulting heating value:

Fuel	Heating Value (Btu/Lb.)
1. JP-4 used to prepare 97% emulsion	19,920
2. 97% emulsion of JP-4	18,950
3. JP-4 used to prepare gelled fuels	20,000
4. 1% gel	19,820
5. 1.5% gel	19,600
6. 2% gel	19,450

A 970 Btu/pound difference can be noted between the 97-percent emulsion and the fuel it was prepared from. This represents a nearly 5-percent reduction in the heating value. The results were rechecked

and found to be accurate within 40 Btu/pound. The gelled fuels, however, show a progressive decline in gross heating value. However, it was not possible to confirm this effect from the engine test run.

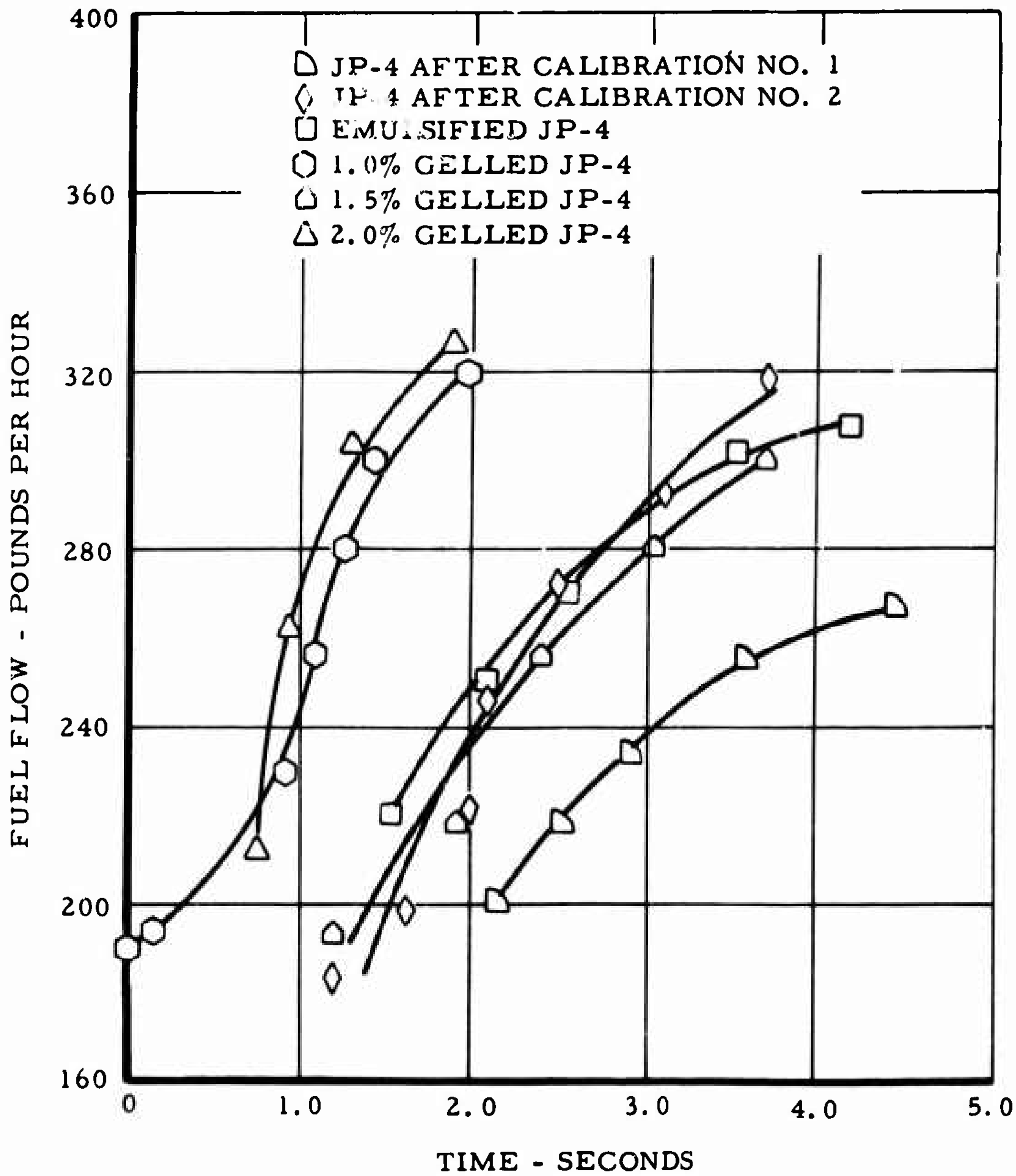


Figure 122. Fuel Flow Acceleration Time.

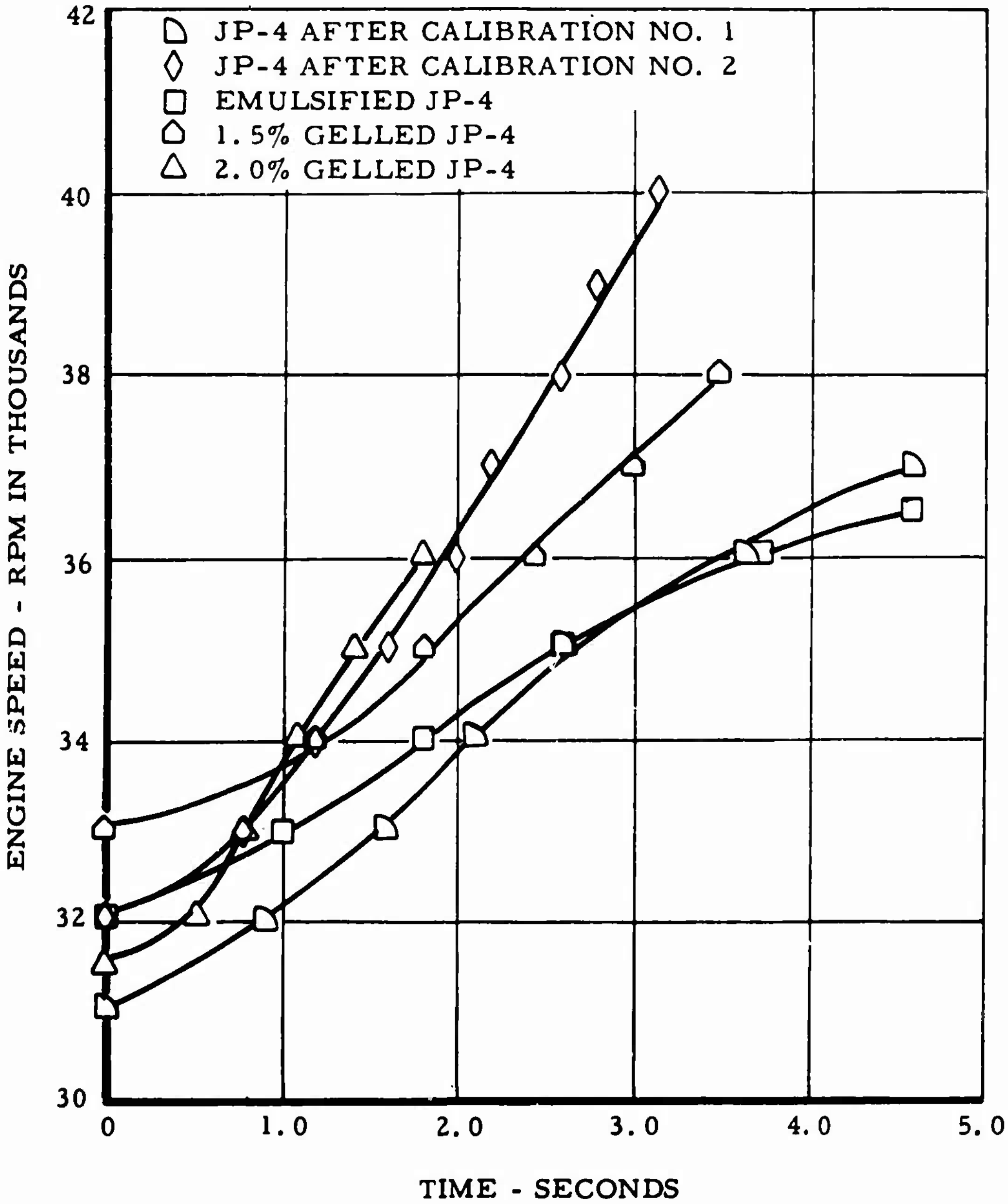


Figure 123. Engine Speed Acceleration Time.

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of burning gelled and emulsified fuels in a gas turbine has been successfully demonstrated in a T72-T-2 Continental Model 217-5 turbine engine. Alkylamide gelled JP-4 fuel solutions with gelling agent concentrations of 1 percent, 1.5 percent, and 2 percent were successfully demonstrated as well as a 97-percent emulsion (0.5-percent emulsifying agent and 2.5-percent water) of JP-4. The feasibility test was performed under essentially standard-day conditions. No variations in temperature or altitude conditions were attempted.

The engine operating characteristics appeared normal with all types of fuels tested. No significant deterioration in performance was detected within the limits of the minimum type of instrumentation used for this study. No apparent combustion differences were observed during the limited testing performed with the test fuels. Satisfactory ignition was obtained on all fuels.

It is feasible to utilize present fuel system concepts with gelled or emulsified fuels. The complete engine fuel system including the engine control was found to perform within acceptable limits and was used without modification, except for filters, for the engine demonstration. Aside from the problems of filtering, the double-element gear type fuel pump required a higher than normal boost pressure to prevent cavitation, when using gelled fuels. A boost of over 10 psig was found to be the usable minimum. Thus new concepts in boost pumps may be necessary to overcome the filter requirements and to supply the additional pressure required to prevent cavitation. Additional work will be necessary to completely define these requirements for a specific system.

The removing of contamination and dirt from gelled and emulsified fuels is a major problem common to both types of fuels. The prime problem is that the usual gravity-density method of separating water, rust, and other contaminants does not work with the semisolid fuels. Rust particles suspended in a clear 2-percent gel solution have shown no trace of settling over an observed 2-month period. The lack of density separation will also mean that most self-cleaning fuel filters depending upon a density separation must be redesigned for continuous operation. A problem likely to be experienced in the filtering of emulsified fuels is a gradual accumulation of water in the filter area due to a partial breakdown of the emulsion.

The gelled fuels tested were not completely stable. Migration of the gelling agent was experienced when filtering the gelled fuels. If the filter element or strainer screen was of too fine a mesh, the fuel would filter out of the gel, leaving the agent behind. The gel on the upstream side of a fine filter (100 microns or less) would become progressively harder as the percentage of agent increased. Gelled fuels with near rubber-like qualities were removed from the filters after laboratory and engine test runs during the program.

It was also impossible to successfully run the engine continuously on either a 1-percent or 1.5-percent gelled fuel which had been aged for over 3 weeks in semiopen containers. This fuel became nonhomogeneous, possibly due to a migration of the gelling agent. It is believed that the hard spots affected the operation of the fuel control; however, the cause of the malfunction was never completely determined. The engine would start, run, and flame out without warning. It was then possible, without altering the test setup, to substitute freshly mixed gelled fuel, and all three fresh fuel mixture percentages, 1 percent, 1.5 percent, and 2 percent, were tested successfully in a routine manner.

The relative safety of the various fuels and other merits should be determined as promptly as possible. It is observed that two types of emulsions were tried with widely different flow characteristics. One of the emulsions supplied could be easily pumped with standard equipment. If this emulsion proved to be equally safe, it would greatly expedite the application of the new fuels.

CONCLUSIONS

1. The feasibility of operating a gas turbine engine on emulsified fuel has been demonstrated in the Continental T-72, General Electric T-64, Lycoming T-53 and T-55, and Allison T-63 turbine engines.

2. The standard engine fuel systems can be used for emulsified fuel with relatively minor adjustments or modifications to the system.

RECOMMENDATIONS

It is recommended that:

1. Further testing be conducted with the engines operating on emulsified fuel for a period of 50 hours or more.

2. This endurance testing include various altitude limits and also cover a range of ambient temperature conditions.

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DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Aviation Materiel Laboratories Fort Eustis, Virginia	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Investigation of the Feasibility of Burning Emulsified Fuel in Gas Turbine Engines

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (Last name, first name, initial)

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1967	216	[illegible]1

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. Task 1F121401A529	USAAVLABS Technical Report 67-24
c. d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Aviation Materiel Laboratories Fort Eustis, Virginia

13. ABSTRACT

This report discusses the results of five different gas turbine engines operating on emulsified JP-4 fuel. Problems associated with using emulsified fuel, and the conclusions and recommendations as they pertain to each individual engine, are given.

The results of these studies indicate that it is feasible to operate a gas turbine engine on emulsified JP-4 fuel. Several areas in which further research is needed, as recognized by the engine companies, are brought out in the report.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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